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Ultraviolet Disinfection of a Secondary Wastewater Treatment Plant Effluent

HydroQual, Inc.
Mahwah, NJ

Prepared for

Municipal Environmental Research Lab.
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16. ABSTRACT
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Second order dose-response relationships were developed and were found to provide a rational expression of the microbial response to ultraviolet dose. The ultraviolet absorbance coefficient, k (cm^{-1}), was found to be an excellent parameter for use in the dose expression and in the design sizing of U.V. systems. Photoreactivation was observed and was significantly dependent upon temperature. The phenomenon could result in an order of magnitude increase in coliform density at a temperature of 20 °C.

The process was determined to be very flexible and simple in operation, requiring minimal maintenance. Costs were estimated to range between 1.2 and 0.8 ¢/m^3 (4.5 and 3.0 ¢/1000 gal) for typical secondary treatment plants with flows between 0.044 and 4.4 m^3/sec (1 and 100 mgd), respectively.

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ULTRAVIOLET DISINFECTION
OF A SECONDARY WASTEWATER TREATMENT PLANT EFFLUENT

By

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Mahwah, New Jersey 07630

Grant No. R-804880

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This study was conducted
in cooperation with
Northwest Bergen County Sewer Authority
Waldwick, New Jersey 07463

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report describes the first full-scale evaluation of ultraviolet light disinfection technology applied to a conventional activated sludge effluent. The findings illustrate the technical feasibility and cost effectiveness of ultraviolet disinfection compared with the more conventional approach, chlorination. The impact will have far reaching effects on municipalities interested in implementing alternative ways of disinfecting secondary effluent.

Francis T. Mayo
Director, Municipal Environmental
Research Laboratory

ABSTRACT

The application of ultraviolet irradiation to the disinfection of a secondary wastewater treatment plant effluent was investigated during a 13 month field study at the Northwest Bergen County Water Pollution Control Plant, Waldwick, New Jersey. The full scale U.V. unit, capable of treating the total plant flow of 15,000 to 30,000 m^3/d was comprised of 400, 85W germicidal lamps. The gravity flow submerged system was retrofitted into an existing chlorine contact chamber.

The experimental program was designed to demonstrate the feasibility of achieving a fecal coliform density of 200 MPN/100 ml by ultraviolet irradiation; to determine the efficiency of ultraviolet disinfection relative to dosage, power consumption, and effluent water quality; and to assess the utility of the full scale unit relative to O&M requirements. The impact of photoreactivation, a repair mechanism unique to ultraviolet irradiation, was investigated during the field program. Uniform procedures for the calculation of dose and the sizing of ultraviolet systems were also developed.

Second order, log transformed linear regression dose-response relationships were developed and were found to provide a rational expression of the microbial response to ultraviolet dose. A dose of approximately 60,000 $\mu W\text{-}sec/cm^2$ was determined to be necessary to achieve an effluent fecal coliform density of 200 MPN/100 ml. The ultraviolet absorbance coefficient, k (cm^{-1}), was found to be an excellent parameter for use in the dose expression and in the design sizing of U.V. systems. Temperature was not found to have a significant impact on the dose-response relationships. Photoreactivation was observed and was significantly dependent upon temperature. The phenomenon could result in an order of magnitude increase in coliform density at a temperature of 20°C.

The process was determined to be very flexible and simple in operation, requiring minimal maintenance. Costs were estimated to range between 1.2 and 0.8 $¢/m^3$ (4.5 and 3.0 ¢/1000 gal) for typical secondary treatment plants with flows between 0.044 and 4.4 m^3/sec (1 and 100 mgd), respectively.

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SECTION 1

INTRODUCTION

The overriding considerations which determine disinfection practices in this country are public health, and the protection of aquatic and human environments. Municipal wastewaters contain many infectious microorganisms, and outbreaks of various infectious diseases, including gastroenteritis, typhoid, and infectious hepatitis, have resulted from drinking and swimming in contaminated waters, and from consuming raw molluscan shellfish harvested from sewage contaminated waters (1). Thus disinfection of domestic wastewaters is widely practiced in this country as a deterrent to the outbreak and spread of waterborne disease.

In the early 1800's, human wastes were collected in cesspools or privy vaults. When these systems were full, they were cleaned and the wastes were discarded on land or into adjacent waterways. The development of large urban population centers in the late 1800's resulted in the replacement of cesspools by sewers. The wastewaters were collected and typically discharged into the nearest waterway. Stream pollution by wastewater resulted in disease outbreaks at points downstream from these raw waste discharges.

The correlation between disease outbreaks and sewage contamination was recognized by 1890, and steps were taken to treat the wastewater prior to its discharge into the waterways, and to treat the drinking water drawn from the waterway. Studies showed that filtration and chlorination of the drinking water supply were effective in reducing disease outbreaks. In Philadelphia, as an example, typhoid fever outbreaks had increased during the period of 1885 to 1906 from 2,000 cases to 10,000 cases per year. With filtration (1906) and chlorination (1913) of the water supply, a dramatic reduction in disease outbreaks occurred. The number of typhoid fever cases had dropped to about 200 cases per year by 1925 (2).

Through the early 1900's, chlorine became an established disinfectant for water supplies and wastewater treatment systems in the United States. The application to water supplies resulted in a dramatic decrease in waterborne disease outbreaks, and a general improvement of the public health (1,3). Craun and

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McCabe reported a decline in the number of waterborne disease outbreaks in this country from an average of 45 outbreaks per year in 1938-40 to an average of 10 outbreaks per year in 1951-55. The average number of outbreaks increased slightly since the 1950's to an average of 14 outbreaks per year from 1966 through 1970. The most common causes of these occurrences were traced to the lack of disinfection of ground water, inadequate disinfection of water and wastewater, and cross connections (4).

DISINFECTION STANDARDS

The individual states have historically controlled wastewater disinfection practices in this country, with emphasis placed on public health considerations. Because of the cost associated with disinfection, the practice has typically been restricted to areas where human contact with wastewater is likely. Disinfection has not been required in many cases where the risk of contact with wastewater is remote.

The passage of the Clean Water Act, PL 92-500, in October 1972, and the subsequent enactment of the Secondary Treatment Information Regulation by the EPA in August 1973, resulted in effluent standards formulated on a national basis (5). A fecal coliform standard was included in the definition of secondary treatment, prompting the imposition of disinfection in all situations, without review of the costs and benefits associated with site specific cases. Upon considerable review, the USEPA officially deleted the fecal coliform standard from the regulation on July 26, 1976, returning the control of disinfection practices to the states (5,6).

Disinfection requirements are now implemented through discharge permits that are issued to individual treatment facilities in accordance with the National Pollutant Discharge Elimination System (NPDES). The NPDES permits set effluent limitations in terms of indicators (i.e. coliform bacteria) of pathogenic contamination. Coliform limitations are normally specific to the desired use of the receiving water, and thereby reflect public health and environmental considerations.

The generally accepted criteria for disinfection, based on water use, are as follows (1,5):

- where shellfish are grown for human consumption, the median coliform densities should be 14 fecal coliforms or 70 total coliforms per 100 ml,

- where whole body contact of a receiving water is desired, the geometric mean over a 30 day period should not exceed 200 fecal coliform bacteria per 100 ml, with a maximum 7-day average of 400 per 100 ml,

- where secondary contact recreation is desired, such as boating, in-stream levels may be from 1,000 to 5,000 fecal coliforms per 100 ml.

DISINFECTION ALTERNATIVES

Disinfection by chlorination became the generally accepted procedure in the United States because of its cost-effectiveness and long proven reliability in meeting bacteriological standards. Recent studies, however, have shown that widespread use of chlorine, in many cases, has resulted in chlorine residuals which are toxic to aquatic life. A study by Brungs concludes that where continuous chlorination is required, total residual chlorine should not exceed 0.01 mg/l for more resistant aquatic biota, or 0.002 mg/l for the protection of most aquatic organisms (7). A study by Ward and Degraeve concluded that chronic exposure to mean residual chlorine concentrations as low as 0.045 mg/l in secondary effluents can adversely impact *Pimephales promelas* (fathead minnows), and concentrations as low as 0.033 mg/l can retard their growth (8).

It has been shown that chlorination of industrially contaminated waters can potentially result in the creation of new toxicants (7). The discovery of carcinogenic and suspected carcinogenic chlorinated hydrocarbons in the water supplies in the lower Mississippi River area stimulated recent concern for the widespread use of chlorine in the disinfection of sewage plant effluents (9).

Another major concern with disinfection by chlorine is a result of recent studies showing that many viruses are resistant to destruction by chlorination. Enteric viruses have been found in chlorinated treatment plant effluents and receiving streams (10). Polio virus and coxsackie A2 virus have been shown to be 7 to 8 times more resistant to chlorine than *Escherichia coli* (11).

Certainly, the benefits and contributions of chlorination to public health cannot be denied, nor should the hasty elimination of chlorination as a disinfection practice be considered. However, in light of the adverse impacts and uncertainties which are now being associated with chlorination, a search for alternative disinfection practices has been undertaken by the USEPA. The primary objective of EPA's Wastewater Disinfection Program is to provide alternatives to current chlorination practices, which will continue the protection of public health from the spread of disease due to point-source discharges of pathogenic microorganisms and viruses. The EPA is pursuing all aspects of this objective with consideration given to the possible formation of toxic by-products and possible adverse environmental impacts from alternative disinfection processes (6).

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Various alternative disinfection technologies are under investigation as to their reliability, effectiveness in reducing pathogenic organisms and viruses, and their overall cost effectiveness. These include improved chlorination management, dechlorination, ozonation, chlorobromination, chlorine dioxide disinfection, and ultraviolet light irradiation. This particular study addresses the use of ultraviolet light as an alternative disinfection process.

DISINFECTION BY ULTRAVIOLET LIGHT

The germicidal effects of ultraviolet radiation are realized when the energy is absorbed by the genetic material of the microorganisms. This absorption of ultraviolet radiation results in death or increased mutation rates of the survivors. The germicidal wavelengths of ultraviolet radiation range from 210 to 310 nm, with maximum absorption by the nucleic acids occurring at 260 nm (12,13). As a consequence, low pressure mercury vapor lamps with their high energy output at 253.7 nm are very efficient as germicidal agents.

When ultraviolet energy is absorbed by the genetic material of organisms, cyclobutane pyrimidine dimers are formed in which neighboring cytosine or thymine moieties are jointed together by a cyclobutane ring. These dimers are the major cause of the lethal and mutagenic effects from ultraviolet radiation. Thymine dimers cause distortions in the DNA that prevent the proper replication of DNA strands, and thus result in death, in mutation of offspring, and in inviable offspring (13,14,15).

A fission of thymine dimers occurs when the injured organisms are exposed to energy in the visible range between the wavelengths 310-500 nm, subsequent to their exposure to ultraviolet irradiation. This repair phenomenon, discovered by Kelner (38), has been termed photoreactivation (13,14,15). Several mechanisms can result in the photoreactivation of microorganisms, the most prominent of which is photoenzymatic repair. Photoreactivation effects have been observed in the cells of many organisms including viruses and phage (if in host cell), bacteria, fungi, higher plants, protozoa, echinoderms, arthropods and in all major groups of vertebrates, except the placental mammals (16). Research studies have shown significant increases in cell viability through photoreactivation, implying the need to consider the phenomenon in the application of ultraviolet disinfection.

All microorganisms contain nucleic acids and are thus susceptible to ultraviolet damage. However, the sensitivity of the organisms vary, depending on the resistance of the organism to ultraviolet energy penetration. Ultraviolet energy must penetrate to the nucleic acids in order to inflict damage. Thus the relative resistance of an organism to ultraviolet damage is

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dependent on the chemical composition of the cell wall and its thickness.

The resistance of an organism is measured by the time it takes to kill a certain percentage of organisms at a specific ultraviolet dosage (17, 18). Among bacteria, gram negative organisms were found to be less resistant to ultraviolet penetration than gram positive organisms. Various studies have examined the relative resistances of microorganisms to ultraviolet destruction. Listed in order of increasing resistance to ultraviolet were *Shigella*, *Proteus*, *Escherichia coli*, *Streptococcus* and *Staphylococcus* (17). Yeast, fungi, and spores are usually more resistant to ultraviolet radiation (14). *Escherichia coli* was found to be equally or more resistant to ultraviolet than *Salmonella typhosa*, *Staphylococcus aureus*, Polio type 1 virus, Coxsackie A2 virus, and Adenovirus type 3 (11).

APPLICATION OF ULTRAVIOLET DISINFECTION TECHNOLOGY

The ultraviolet transmittance, lamp design, maintenance, and absence of a residual have all been significant factors in the application of ultraviolet disinfection technology. Since wastewaters are considered homogenous relative to contaminant concentration, an effective ultraviolet disinfection system must transmit the germicidal rays through the entire waste stream. This is achieved by reducing the depth (or distance) of wastewater from the ultraviolet source, by providing enough turbulence to mix the wastewater stream, and by lengthening the ultraviolet exposure time.

Provisions must be made to keep the lamp surface clean, and therefore, maintain maximum transmittance of ultraviolet light. Historically, ultraviolet disinfection has been applied to relatively clear waters because dissolved organics and solids, present in low grade wastewaters, readily absorb the germicidal energy, resulting in decreased penetration and less disinfecting potential. However, improved designs in ultraviolet disinfection equipment are able to compensate for water quality considerations.

Ultraviolet disinfection does not leave a residual in the treated stream, and therefore its applicability to potable water treatment is limited. However, the lack of a residual can be a desirable characteristic when discharging treated wastewaters to natural water receiving streams.

Ultraviolet light, generated with mercury vapor lamps, was used in the early 1900's to sterilize drinking water. Chlorination systems soon replaced ultraviolet disinfection systems in public water supplies because chlorination was easier to control, more economical, and allowed for maintenance of a residual disinfectant in the water distribution system. Ultraviolet disinfection has been used to purify small drinking water supplies. In a study by Huff, Smith, Boring and Clarke, ultraviolet disinfection proved to be effective in treating potable water supplies on board ships (19). Approximate dosages studied varied from 4,000 to 11,000 μWatt-sec/cm^2. These doses were estimated with an intensity meter at the side of the unit. Under design conditions (dose of 11,000 μWatt-sec/cm^2), 99.9999 percent kill of E. coli, A. aerogenes and S. faecalis was achieved, with effluent counts consistantly below 1 per 100 ml. Turbidity levels up to 5 NTU did not decrease treatment efficiency below the acceptable limits.

The need for a continuous supply of sea water to purify oysters prompted an ultraviolet disinfection study by Kelly (17). The system utilized by Kelly consisted of a trough with thirteen 30 Watt germicidal lamps suspended 14 cm above the liquid surface. To obtain the stated water quality, Kelly estimated that a dose of 57,600 μWatt-sec/cm^2 was required. The pilot scale study demonstrated that, with proper maintenance, the ultraviolet unit would operate dependably. With raw water fecal coliform levels ranging up to 2,400 per 100 ml, and turbidities up to 20 NTU, only 5% of the 91 samples showed the presence of coliforms after ultraviolet irradiation. The maximum observed effluent fecal coliform density was 0.2 per 100 ml.

Hill, Hamblet, Benton, and Akin conducted a study with eight virus cultures to examine the inactivation rate in continuously flowing sea water by the Kelly-Purdy ultraviolet treatment unit (20). Virus cultures were mixed with sea water and placed in petri dishes, with a liquid depth of 0.6 cm. The ultraviolet lamps were suspended 14 cm above the plates and exposure times to obtain various percent kills were determined. The exposure times to obtain effective disinfection (99.9% reduction) at an applied intensity of 1160 μWatt/cm^2 were as follows:

Virus	Time (seconds)
Poliovirus 1	28
Poliovirus 2	31
Poliovirus 3	27
Echovirus 1	28
Echovirus 11	31
Coxsackievirus A-9	31
Coxsackievirus B-1	40
Reovirus 1	40

The study concluded that ultraviolet radiation could be very effective in treating estuarine water for viral inactivation.

EPA-287 (Cin.)
(4-76)

Ultraviolet disinfection has been used successfully in purifying hatchery waters. The relative clarity of these waters results in a high transmittance of ultraviolet wavelengths through the water and, therefore, increases the disinfection efficiency. The application of ultraviolet disinfection to hatchery waters is ideal because the process leaves no residuals that could be harmful to the fish. At the Dworshack National Fish Hatchery in Ahsahka, Idaho, a combination of biofilters and ultraviolet lights were used to purify the hatchery waters. A drawback noted for the system was the algae buildup on the lamps which reduced the ultraviolet output (21). The units were not equipped with an automatic cleaning system. The Greenlake National Fish Hatchery in Ellsworth utilizes a 0.96 m^3/sec ultraviolet disinfection system for successful treatment of the hatchery waters (18).

Recent improvements in ultraviolet lamps and ultraviolet system designs have made the process a viable alternative to chlorine disinfection of wastewater treatment plant effluents. An ultraviolet disinfection pilot system was utilized to disinfect the effluent of an activated sludge plant which discharged to shellfish waters in St. Michaels, Maryland (22). To open the waters to the harvesting of shellfish, continuous disinfection was required to yield total coliform densities less than 70 per 100 ml and to significantly reduce viral populations. The 230 liter pilot ultraviolet disinfection chamber contained 16 G36T-6, 36-Watt germicidal lamps. The rated germicidal output of each lamp was 10.4 Watts. The waste depth in the trough was approximately 8 cm, and the lamps were suspended 6.7 cm above the liquid surface, with reflective backing to direct as much light to the water as possible. The ultraviolet transmittance through the water, which had an average chemical oxygen demand (COD) of 45 mg/l, was on the order of 65%. First order reductions in total coliform and bacteriophage densities were observed with a tailing effect after 99.99% kill of the coliforms. The average dose required to reduce coliform densities to 70 MPN/100 ml or less was estimated by the investigators to be 25,000 μWatt-sec/cm^2. Photoreactivation of coliforms and bacteriophage (inside their hosts) was observed in specific controlled tests. The report concluded that ultraviolet disinfection would be practicable for application to well-controlled activated sludge plant effluents.

A 3.2 liter/sec ultraviolet disinfection unit was used to evaluate ultraviolet disinfection of the final effluent from the recently upgraded 26th Ward step aeration plant in Brooklyn N.Y. (23). The 47.3 liter unit contained nine, 40-Watt submerged lamps, with the wastewater flowing parallel to the lamps. The total energy input was maintained at 7.7 Watts per liter, resulting in a germicidal input of 2.6 Watts per liter. Exposure times and water quality were varied. Effluent fecal coliform densities of 200/100 ml or less were typically achieved with suspended solids less than or equal to 20 mg/l. Coliform reduction was found to be relatively insensitive to exposure time over the range of times studied (8.5 to 25 seconds). The fecal coliform reduction was found to be highly dependent on the water quality. Results indicated that the ultraviolet disinfection process would satisfactorily disinfect step aeration effluents.

A research project was conducted in Dallas, Texas to study the feasibility of ultraviolet disinfection of treated municipal wastewater effluents to achieve fecal coliform densities less than 200 MPN/100 ml (24). Two ultraviolet disinfection systems were evaluated. The first unit, based on the Kelly-Purdy design, consisted of a shallow exposure tray, 185 cm long, 92 cm wide and 9.2 cm deep, with thirteen, 30-Watt ultraviolet lamps (G30T8) mounted above the chamber. Flow was perpendicular to the lamps. The second system, an Ultraviolet Purification Systems Model EP-50 unit, consisted of nine 40-Watt lamps (14.8 Watts at 253.7 nm) submerged in a 53.6 liter chamber. The waste flow, in this case, was parallel to the lamps.

The shallow tray exposure chamber was found to be inefficient in the utilization of the full lamp output. The study concluded that exposure chambers utilizing submerged lamps were more effective for disinfection of secondary effluents. Average ultraviolet doses in the submerged system which were reported by the investigators to achieve adequate kills were from 30,000 to 35,000 µWatt-sec/cm^2. The average intensity in the system was estimated by constructing iso-intensity lines across a cross section of the unit. Suspended solids and turbidities of the waste ranged from 5 to 50 mg/l and 0.5 to 12 NTU, respectively. Over the range of water qualities studied, these factors did not appear to affect the ultraviolet transmittance significantly.

A study was conducted in Syracuse, N.Y. to determine whether ultraviolet disinfection could be applied to combined sewer overflows following some level of suspended solids removal (25). One liter samples were irradiated in a bell jar vessel in which the walls were equidistant (5.7 cm) from the ultraviolet lamp. The ultraviolet lamp was a PCQ 9 G-1, 17.8 cm photochemical immersion lamp. The intensity output at the surface of the lamp was calculated to be 5800 µWatt/cm^2. To reach the desired criteria of 2,400 total coliforms/100 ml, the researchers estimated that a dose of 500,000 µWatt-sec/cm^2 was required. The study concluded that ultraviolet disinfection of combined sewer overflows was feasible, and left no residual toxic effects.

A study conducted at the University of North Carolina, Chapel Hill, investigated two generic U.V. disinfection units, utilizing contact stabilization effluent from the Sandy Creek plant in Durham, North Carolina (26). The first unit was based on the close spaced, or "thin film" concept and contained fourteen, 25-Watt submerged lamps at nominal spacings of 1.25 cm. The second unit utilized six, 40-Watt, widely spaced lamps submerged in an eleven liter exposure chamber. Significant differences in germicidal efficiency were noted for the two systems. This was attributed to hydraulic short circuiting occurring in the thin-film system, and not to any basic design difference in the thin versus thick film systems. The study also reported significant photoreactivation in U.V. irradiated samples which had been exposed to sunlight for 45 minutes at 25°C. Total coliforms were found to increase in density an average of 1.4 orders of magnitudes. The degree of photoreactivation was reduced at lower temperatures.

PROJECT BACKGROUND

The results of a full-scale ultraviolet disinfection demonstration project conducted at the Northwest Bergen County Water Pollution Control Plant, Waldwick, New Jersey are presented in this report. The prototype full scale ultraviolet system was tested on a conventional activated sludge plant effluent to determine the system's reliability in achieving desired coliform levels, it's maintenance and operational requirements, and the process costs relative to alternative disinfection procedures. Funded jointly by the USEPA (MERL), Cincinnati, Ohio, and the Northwest Bergen County Sewer Authority, this project represented state-of-the-art ultraviolet disinfection technology, and was a significant advancement for EPA's Research and Development goal of fostering the development of alternatives to chlorine disinfection technology.

HydroQual, Inc., Mahwah, N.J. (formerly Hydroscience, Inc., Westwood, N.J.), was the principal investigator and was responsible for the technical design and performance of the project. The operation of the system and design of the experimental program was under the direction of HydroQual personnel, who were onsite to collect samples, to conduct all analyses, to perform field measurements and determinations, and to document the results of all analyses and field measurements. The firm was responsible for the analysis and interpretation of all the data collected during the program, and for the economic analysis of the U.V. disinfection process.

Pure Water Systems, Inc. (PWS), Fairfield, New Jersey provided the prototype disinfection system, on a rental basis, and was responsible for the installation of the unit at the NW Bergen plant. PWS provided operation and maintenance services throughout the study period, and under the direction of HydroQual, Inc., was responsible for unit metering and upkeep requirements. Pure Water Systems supplied estimates of equipment costs for their specific disinfection systems based on operating requirements derived during the experimental phase.

PROJECT OBJECTIVES

Ultraviolet irradiation has been shown to be an effective disinfecting agent when properly applied. This project studied the application of ultraviolet disinfection to conventional municipal activated sludge effluents. The objectives were:

- to demonstrate the feasibility of achieving a coliform density of 200 MPN/100 ml by ultraviolet light disinfection of a conventional municipal wastewater treatment plant effluent,
- to determine the efficiency of ultraviolet light disinfection of a full scale secondary treatment plant effluent relative to dosage requirements, power consumption, and effluent water quality requirements,
- to determine the utility of a full scale ultraviolet light disinfection unit in the treatment of a municipal secondary treatment plant effluent relative to operational, maintenance, and environmental requirements,
- to estimate the capital, operational, and maintenance costs to implement ultraviolet disinfection for municipal treatment plants of varying sizes, and to compare on a cost-effective basis with disinfection by alternative processes.

SECTION 2

CONCLUSIONS

The results of a full scale experimental study demonstrated that ultraviolet irradiation is a viable, effective, and practical disinfection procedure for application to secondary wastewater treatment plant effluents. The process is capable of consistently meeting typical secondary effluent coliform criteria on a long term basis. A dose of approximately 60,000 μW-sec/cm^2 was required to meet an effluent fecal coliform density level equal to or less than 200 MPN/100 ml in the wastewater studied. For a typical secondary effluent with an average U.V. absorbance coefficient of 0.5 cm^{-1}, the average power requirement to meet this density level is approximately 3.2 watt-hr/m^3.

The second order relationship,

$$\frac{dN}{dt} = yN^2I$$

where:

N = Density at time, t

I = Average U.V. intensity in wastewater

y = Rate constant

was found to provide a more significant expression of disinfection performance than the traditional first order survival expressions. The equation can be integrated to yield:

$$\frac{1}{N} - \frac{1}{N_o} = yIt$$

where:

N_o = Initial fecal coliform density

t = Time of exposure at average intensity

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In cases where $N_o >> N$ (e.g. secondary effluent disinfection applications), the initial density term can be ignored and the expression reduces to,

$$\frac{1}{N} = yIt$$

Linear regressions (by the least squares approximation) of the log transformation of this expression provides an excellent correlation of log effluent density (N) and log dose (It). Temperature, within the range of 8° C to 24° C, was not found to affect the dose-response relationship.

The dosage expression utilized in this study provides a rational parameter upon which to base the design sizing of an ultraviolet disinfection system. The procedure to compute the dose delivered to the wastewater is based on the physical aspects of a lamp system, including lamp rating, dimensions, and geometric placement, and on the characteristics of the wastewater to be treated, including the flow rate and its ultraviolet energy absorbance properties.

The ultraviolet absorbance coefficient, k, which was measured at a wavelength of 254 nm, is a useful parameter for the design, control, and monitoring of ultraviolet disinfection processes. The parameter correlates well with routine wastewater parameters such as chemical oxygen demand (COD), suspended solids (SS), turbidity, and coliform density, and serves as a primary measure of U.V. intensity attenuation within the wastewater medium.

Ultraviolet irradiation, when delivered in doses appropriate to disinfection processes, does not appear to have any significant impact on the wastewater quality parameters COD, total organic carbon (TOC), SS, turbidity, U.V. absorbance, color, total Kjeldahl nitrogen (TKN), NH_3-N, NO_2-N, and NO_3-N.

Photoreactivation, a term used to describe a repair mechanism of the exposed bacterial cell, and which requires energy in the visible light range, causes a significant increase in cell number subsequent to ultraviolet irradiation. The degree of repair is temperature dependent, and is a constant factor increase over the immediate post-irradiation cell density. At a temperature of 10°C, this factor is approximately 2, while at a temperature of 20°C, cell viability can increase by a factor of approximately 10 after exposure to sunlight.

The static bottle test is an effective and practical bioassay procedure which provides a reasonable approximation of the kinetics associated with photoreactivation. The test is

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relatively simple and offers the benefit of being controllable under standard test conditions.

Photoreactivation is a controllable phenomenon. If it is to be accounted for in disinfection applications, the ultraviolet dose would have to be increased to such a degree that, including post-irradiation repair, the density will be less than the prescribed criterion.

The ultraviolet lamp system used in these studies is flexible and simple in its operation, and should require minimal maintenance. Lamp life appears to be in the order of 9 months. Quartz sleeves and lamp ballasts have an approximate replacement cycle of 3 to 4 years. The ring glands on the mechanical wiper require replacement approximately once each year.

The mechanical wiper system appears capable of maintaining clarity and preventing the buildup or accumulation of a film on the quartz surface. If the wiper mechanism is shut-off for an extended period of time, however, and a film develops on the surface, the wiper does not appear capable of restoring the quartz to its original clarity. The quartz then requires cleaning with an acid solution.

Ultraviolet disinfection is comparable in cost to chlorination, chlorination/dechlorination, and chlorbromination. The process is more cost-effective than ozone disinfection. Costs are estimated to range between 1.2 and 0.8¢/m^3 (4.5 and 3.0¢/1000 gal) for secondary treatment plants with flows between 0.044 and 4.4 m^3/sec (1 and 100 mgd), respectively. If the sizing of a U.V. system must account for photoreactivation, the costs of the U.V. process are comparable to present cost estimates of ozone disinfection.

SECTION 3

RECOMMENDATIONS

The procedures for dose calculation and system design should be confirmed and refined in future ultraviolet disinfection applications. The ultimate objective must be to define a standard ultraviolet dosage measurement and/or computation procedure, and to establish a unified design protocol for alternative U.V. systems, particularly in the specifications of system performance, system maintenance, and lamp battery design. Such standards are lacking at present in the area of wastewater disinfection.

A comparative analysis of alternative system designs is warranted due to the diversity of the present U.V. equipment market. This diversity ranges from variations in lamp placement ("thin" vs. "thick" film), contact (submerged) and non-contact systems, to several mechanisms for maintaining quartz clarity (mechanical wiper, chemicals, sonication). Again, such an analysis should be directed to the development of a uniform design procedure and a standard method for calculation and/or measurement of U.V. dose.

Work should continue on the efficiency and performance of U.V. disinfection systems under variable water quality conditions, particularly for application to stormwaters and to combined sewer overflow (CSO) wastewaters.

The investigation of the photoreactivation phenomenon and its implications should continue. This work should also include the analysis of repair capabilities of specific pathogenic organisms.

SECTION 4

DESCRIPTION OF EXPERIMENTAL FACILITIES

SITE DESCRIPTION

The site of the U.V. installation was the Northwest Bergen County Water Pollution Control Plant, located in Waldwick, New Jersey. Figure 1 presents a site schematic of the plant. It is a conventional air activated sludge system with a design capacity of 30,000 m^3/day (8 mgd), and an average yearly flow, at present, of approximately 18,900 m^3/day (5 mgd). Completed in 1968, the plant is a modern, efficient facility discharging a well treated secondary effluent to Ho-Ho-Kus Brook, a water quality stream.

The plant receives domestic wastewaters and a minor industrial input, and is on occasion substantially impacted by high stormwater inflow. It presently discharges an effluent representative of advanced secondary treatment. Table 1 presents monthly averages of the plant performance during the 13 month experimental period. These data were provided by the Northwest Bergen WPCP, and typically represent 24 hour composites. Note the high stormflow periods during late winter and early spring, and the operation of the plant in a nitrification mode during the warm temperature months (April thru September).

The plant is equipped with dual chlorine contact chambers (Figure 1) and under present flow conditions, one has remained inactive. This situation provided an ideal location for the installation of the gravity feed U.V. disinfection system. A plan view of the existing chlorine contact chambers is presented in Figure 2, which also shows the overall ultraviolet system installation. The active chlorine contact chamber is shown on the left. The chamber on the right was modified to accept the ultraviolet system. Flow from the secondary clarifiers is directed to a common influent channel where flow to either contact chamber is controlled by sluice gates. The chlorine diffusers, normally located in the influent channel, were relocated to the head end of the active chlorination chamber, and approximately 6 meters downstream of the U.V. disinfection system. Since the plant's NPDES discharge permit required maintenance of a chlorine residual, the State of New Jersey

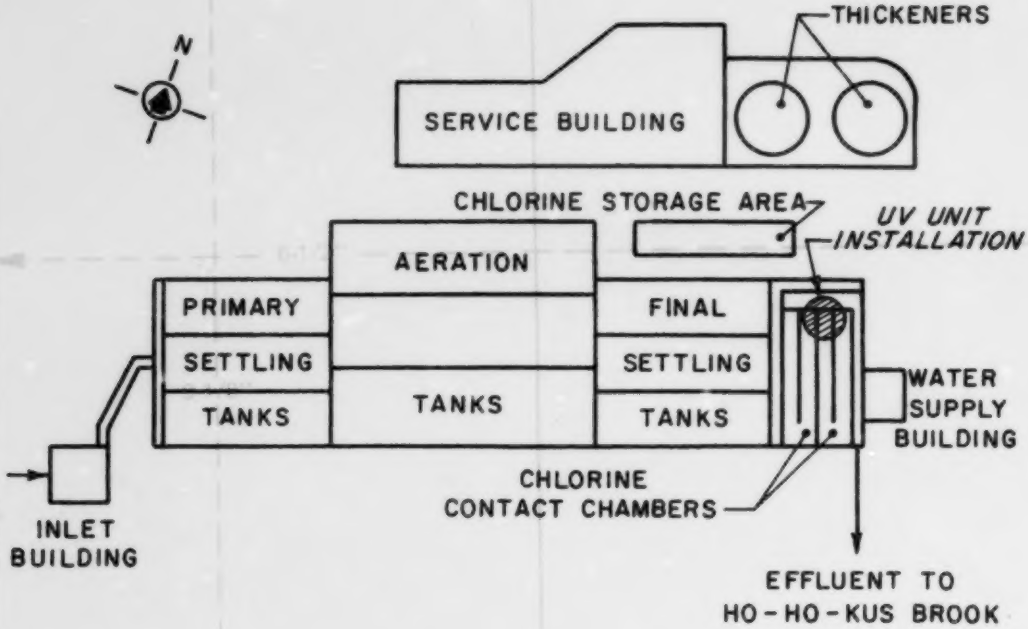
N
THICKENERS
SERVICE BUILDING
CHLORINE STORAGE AREA
UV UNIT INSTALLATION
AERATION
PRIMARY
SETTLING
TANKS
TANKS
FINAL
SETTLING
TANKS
WATER SUPPLY BUILDING
CHLORINE CONTACT CHAMBERS
INLET BUILDING
EFFLUENT TO HO-HO-KUS BROOK

Figure 1 . Site schematic of the N.W. Bergen Water Pollution Control Plant.

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TABLE 1

SUMMARY OF NW BERGEN PLANT PERFORMANCE
(Monthly Averages of 24 Hour Composite Samples)

Month	Flow	Influent (mg/l)			Effluent (mg/l)		
	m^3/d (mgd)	BOD_5	SS	TKN	BOD_5	SS	TKN
March 1978	20,960 (5.5)	190	219	35	12	13	25
April	19,900 (5.3)	179	222	32	5	5	21
May	19,700 (5.2)	180	189	34	4	5	14
June	18,100 (4.8)	195	246	39	6	5	12
July	14,000 (3.7)	231	312	42	6	4	10
August	15,500 (4.1)	187	237	33	4	3	10
September	16,300 (4.3)	195	289	42	4	4	11
October	15,900 (4.2)	231	308	45	5	4	11
November	15,500 (4.1)	113	302	47	5	4	25
December	16,300 (4.3)	244	305	47	6	3	24
January 1979	22,300 (5.9)	193	176	33	6	4	20
February	19,900 (5.3)	168	181	39	9	10	22
March	23,800 (6.3)	128	151	27	4	4	16
April	20,900 (5.5)	155	190	37	6	5	20
Average	18,500 (4.9)	185	238	38	5.9	5.2	17.2

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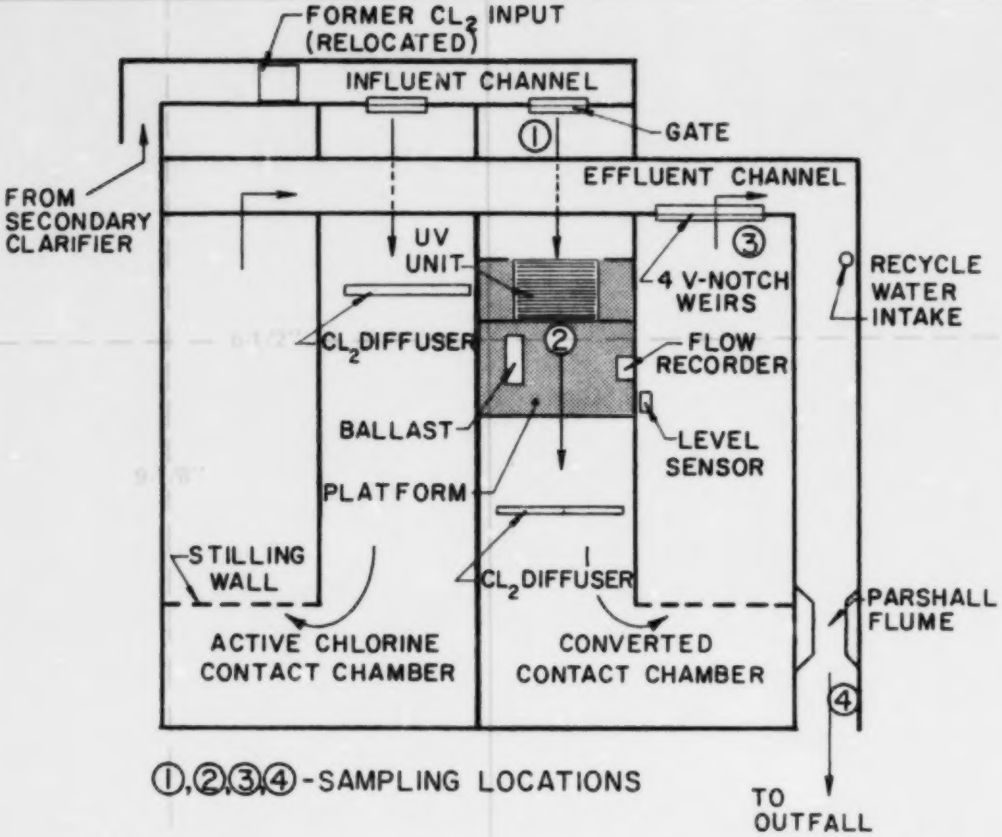
FORMER CL_2 INPUT (RELOCATED)
INFLUENT CHANNEL
GATE
①
EFFLUENT CHANNEL
FROM SECONDARY CLARIFIER
UV UNIT
③
4 V-NOTCH WEIRS
RECYCLE WATER INTAKE
CL_2 DIFFUSER
②
FLOW RECORDER
BALLAST
LEVEL SENSOR
PLATFORM
STILLING WALL
CL_2 DIFFUSER
PARSHALL FLUME
ACTIVE CHLORINE CONTACT CHAMBER
CONVERTED CONTACT CHAMBER
④
①,②,③,④ -SAMPLING LOCATIONS
TO OUTFALL

Figure 2. Plan view of ultraviolet unit installation.

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required chlorination of the U.V. irradiated effluent prior to discharge.

The chlorine contact chambers each have a center stilling wall. The total distance traversed in each is 51.2 meters. The channels have a width of 4.0 meters and a depth of 3.0 meters. Four 90°V-notch weirs were installed at the discharge location of the chamber to measure the flow thru the U.V. system. Flow rate was continuously recorded by a Pro-Tech flow sensor (bubbler) and recorder. The level sensor was located in a stilling well, approximately 3.0 meters upstream of the V-notch weirs.

UNIT INSTALLATION

A cutout view of the contact chamber is presented on Figure 3 and shows the installation of the U.V. lamp battery. Two 15 cm wide reinforced concrete webs provided support. A sump pump was placed between the webs to keep the space dry. The lamp battery itself was supported by two steel bulkheads set into the concrete webs. An air seal, similar to a rubber inner tube, was located along the perimeter between the bulkhead and concrete webs. The figure also shows placement of the mechanical wiper and the pneumatic cylinder which drove the wiper.

Figure 4 presents a cross-sectional view and a hydraulic profile of the installation. As shown, the lamp battery constricts the flow thru the chamber. Velocity profiles taken at the exit of the system indicated good flow distribution across the unit. Tracer studies were conducted with lithium chloride and rhodamine WT to calibrate the V-notch weir flow measurement. Figure 5 presents the flow curve relating depth upstream of the V-notch weirs to flow rate. The figure also shows the head loss experienced thru the lamp battery as a function of flow. The head loss was approximately 10 to 15 cm at typical flow rates, between 19,000 and 23,000 m^3/day.

UNIT DESCRIPTION

A summary of the U.V. unit specifications is presented in Table 2. The prototype was developed and manufactured by Pure Water Systems, Inc., Fairfield, N.J. The system (Model PWS SE-7.5) had a total of 400 germicidal lamps arranged in banks of 80, 60, 60, 60, 60, and 80 lamps each. Each of the 6 banks was individually controlled for on/off operation and the voltage to the total lamp battery could be varied from 40 to 100%.

Each lamp was 156 cm long, and had an effective arc length of 147 cm. The lamps (PWS-L60) were 85 watts nominal, and had a rated germicidal (at 253.7 nm) output of 30 watts. The lamp diameter was 1.9 cm, and each lamp was jacketed in a quartz sleeve with a 2.3 cm outer diameter. Each lamp was monitored

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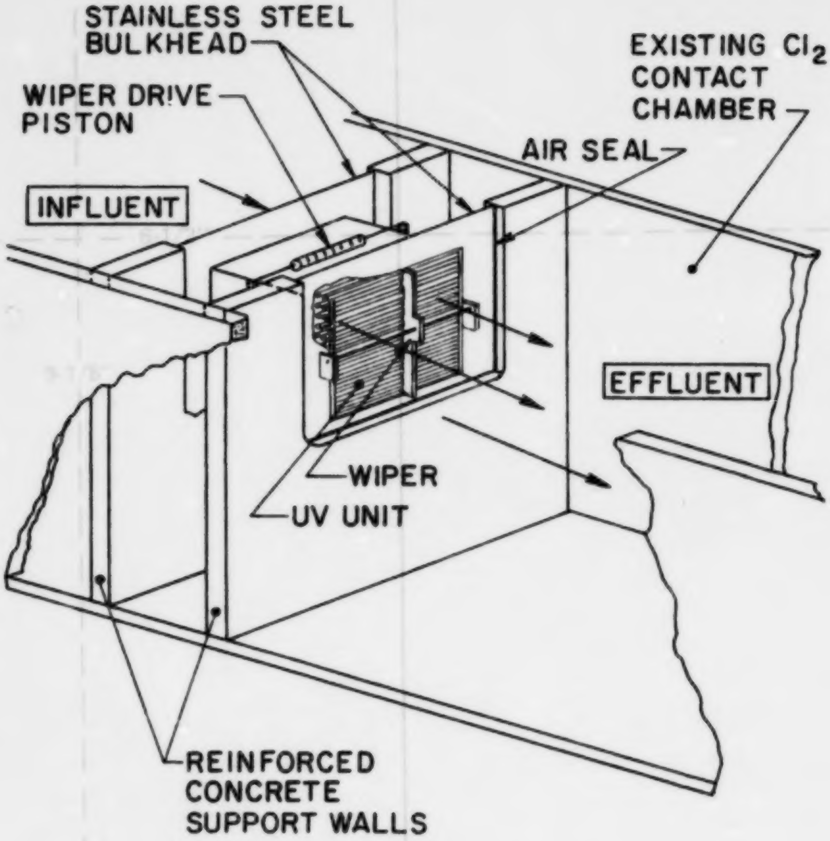
STAINLESS STEEL BULKHEAD
EXISTING Cl_2 CONTACT CHAMBER
WIPER DRIVE PISTON
AIR SEAL
INFLUENT
EFFLUENT
WIPER
UV UNIT
REINFORCED CONCRETE SUPPORT WALLS

Figure 3. Ultraviolet disinfection unit installation.

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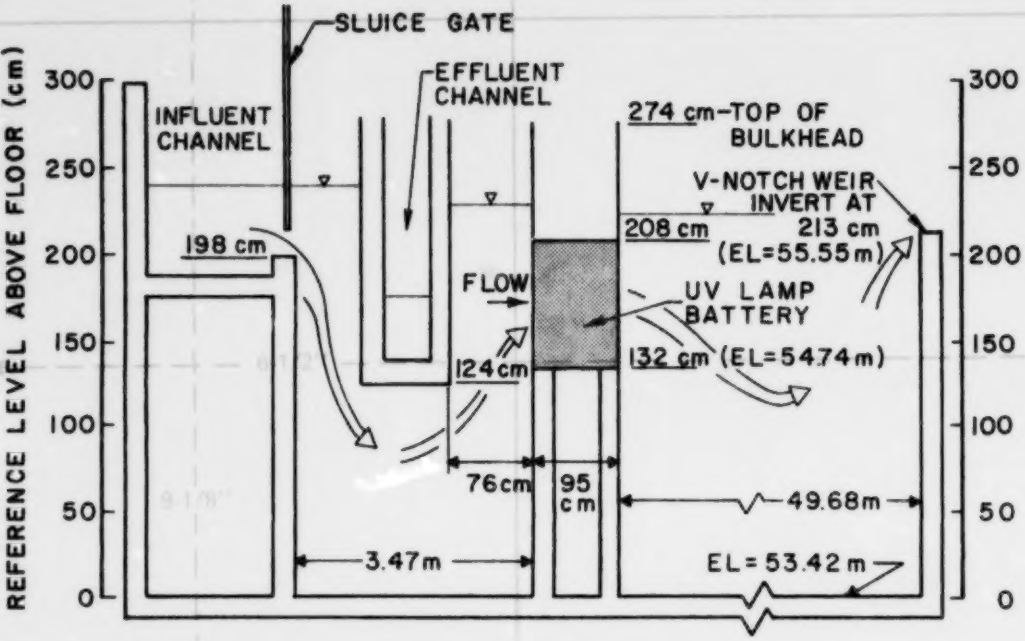
SLUICE GATE
EFFLUENT CHANNEL
INFLUENT CHANNEL
274 cm–TOP OF BULKHEAD
V-NOTCH WEIR INVERT AT 213 cm (EL=55.55 m)
198 cm
208 cm
FLOW
UV LAMP BATTERY
124 cm
132 cm (EL=54.74 m)
76 cm
95 cm
49.68 m
3.47 m
EL=53.42 m
REFERENCE LEVEL ABOVE FLOOR (cm)
300
250
200
150
100
50
0

NOTE: NOT DRAWN TO SCALE

Figure 4. Hydraulic profile of UV disinfection system

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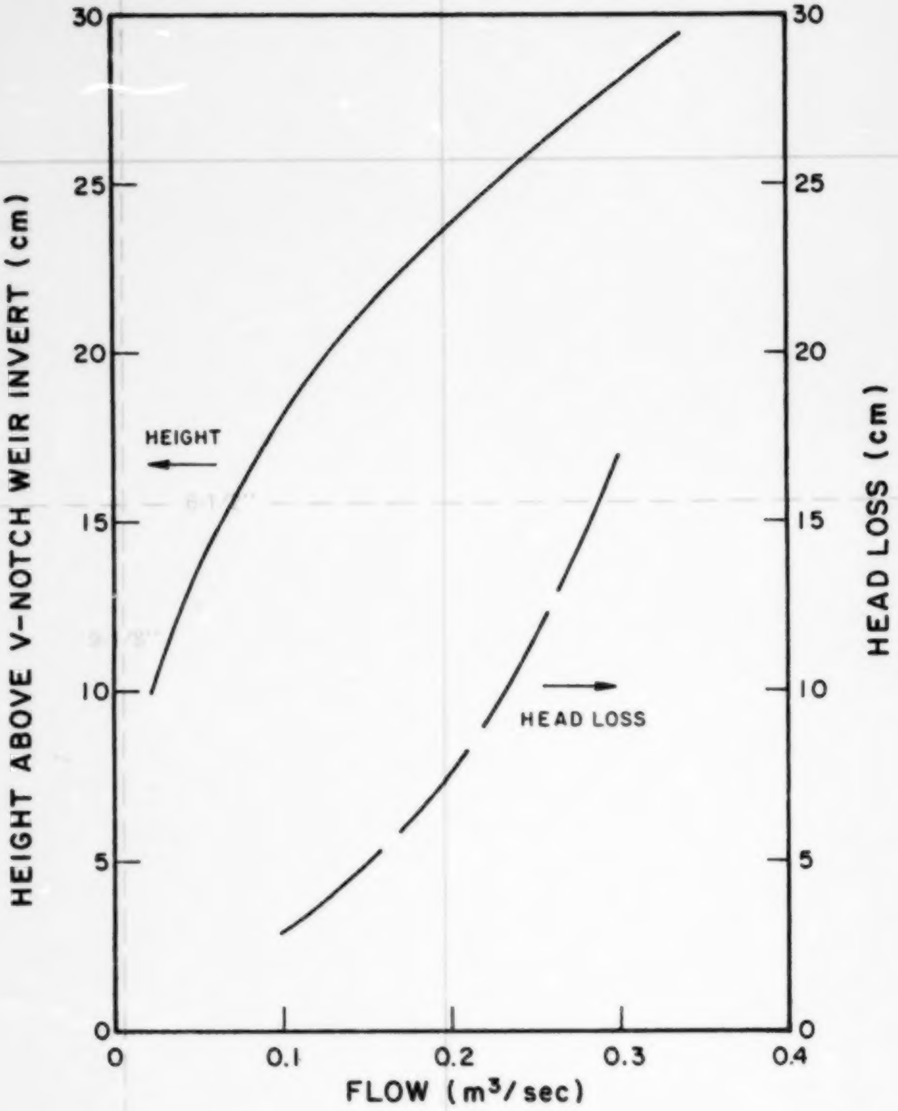

Figure 5. Flow, head loss, and v-notch weir calibrations.

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TABLE 2

SUMMARY OF ULTRAVIOLET UNIT SPECIFICATIONS

Model: PWS SE-7.5

Lamps: 85W PWS-L60, 30W output at 253.7nm
400 Total
Effective arc length per lamp, 147 cm
Quartz jacketed, 2.3 cm outer diameter

Total effective arc length: 589 meters

Total power: 34 KW

Operating voltage: 480 VAC/60 HZ/3 Ph

Lamp battery shut-offs in 1/6 increments

Power variability: 40 to 100% (variac)

Dimensions of lamp battery: 70 x 70 x 152 cm

Void volume: 0.49 m^3

Head loss: Approximately 15 cm at 21,000 m^3/day

Mechanical wiper: Elastomeric glands with cable drive off pneumatic cylinder

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individually by incandescent pilot lights, housed in the lamp ballast cabinet, located on the work platform above the submerged lamp battery. The total effective arc length of the unit was 589 meters. Total nominal power consumption was estimated at 34 KW, at an operating voltage of 480 V (60 HZ/3 PH).

The work platform also held the flow recorder, and the protective housing for the U.V. system. The power supply and Variac voltage regulator were housed in an existing building near the chlorine contact chambers.

The overall dimensions of the lamp battery were 70 x 70 x 152 cm, and the computed void volume was 0.49 m^3. The mechanical wiper was a 304 stainless steel support frame, with replaceable elastomeric glands fitted over each of the quartz tubes. The wiper was cable driven at a variable stroke rate (6 strokes/hour was the typical rate used during the study) by a pneumatic cylinder.

The lamp placement is presented schematically on Figure 6. A feature of the ultraviolet unit is the utilization of the "thin film" concept, which is induced by the spacing of the lamps. The nominal liquid film thickness was 0.625 cm for this particular unit. This is defined as one-half the minimum distance between any two quartz surfaces.

Servicing for this particular installation (lamp replacement, etc.) required pulling the unit up and out of the chamber. This was facilitated by a winch harness and pulley supported by a steel frame directly above the U.V. unit installation.

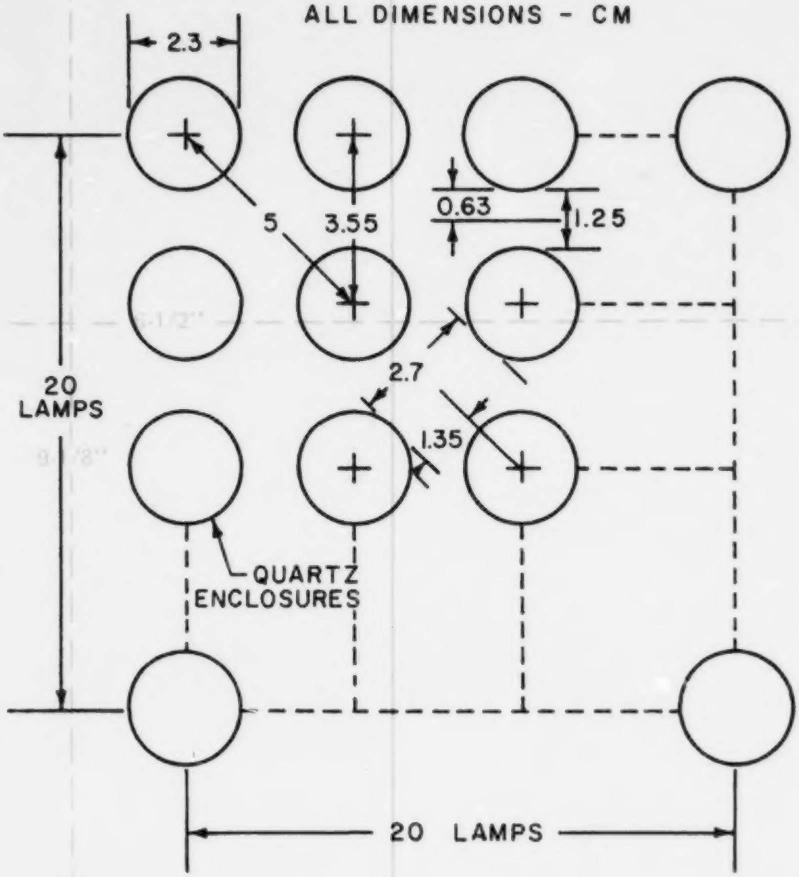
ALL DIMENSIONS - CM
2.3
5
3.55
0.63
1.25
20 LAMPS
2.7
1.35
QUARTZ ENCLOSURES
20 LAMPS

Figure 6. Ultraviolet disinfection unit lamp placement

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SECTION 5

EXPERIMENTAL PROGRAM AND PROCEDURES

The experimental program and procedures used in the U.V. disinfection study are discussed in this section. An overview of the experimental program is presented, and discussions of sampling procedures, and analytical and metering techniques are included.

EXPERIMENTAL PROGRAM

The installation of the pilot system was accomplished between November 1977 and February 1978. The field study, which began in March 1978, was designed to demonstrate the feasibility of achieving a fecal coliform density of 200 MPN/100 ml by ultraviolet radiation; to determine the efficiency of ultraviolet disinfection relative to dosage requirements, power consumption, and effluent water quality requirements; and to assess the utility of the full scale disinfection unit relative to operational, maintenance, and environmental requirements.

Preliminary testing under various unit operational modes was conducted during March and April 1978. The flexibility of the U.V. system operation was established, and laboratory procedures were tested. This same period was used to "debug" the U.V. system and thus assure reliable operation during the subsequent phases of the experimental program.

Although the focus of this study was directed to the sensitivity of the coliform bacteria to ultraviolet light, a short term study was conducted by the Carborundum Company, under a separate grant from the EPA, to investigate the virucidal capabilities of the U.V. system. This was one aspect of a study to evaluate virus inactivation by various disinfection alternatives. Operation of the U.V. unit was held constant during a four week period in April and May 1978 while the influent and effluent were sampled and analyzed for viral densities. The dosage application during the period was relatively high, yielding effluent fecal coliform levels which were consistently less than 20 MPN/100 ml. The results of this investigation have been presented elsewhere (27).

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A second peripheral study, which involved sampling the NW Bergen installation, was conducted by the Oak Ridge National Laboratory. This study evaluated the effects of various disinfecting agents, including ultraviolet light, on non-volatile organics in wastewater effluents (28). Studies by the Oak Ridge Laboratory also investigated the mutagenic activity of these non-volatile organics (29).

During the period June through August 1978, the interdependence of the U.V. unit operational modes, specifically the applied voltage, flow, and the number of lamps engaged, was studied relative to germicidal efficiency. These operations were alternately varied to determine their relative impacts on applied dosage and, consequently, on disinfection efficiency. A wide range of dosages were monitored during this phase of the program, allowing reasonable dose-response relationships to be determined for both total and fecal coliform.

Steady state operation was initiated in October 1978 and was maintained through April 1979, during which performance and operational reliability of the disinfection system were evaluated. The unit was continuously operated and monitored at a selected operational mode (i.e. dose level), which would provide an effluent coliform density less than 200 MPN/100 ml. During the last 3 months of this period, February through March 1979, the applied dose was intermittently varied from the pre-selected continuous dose level to confirm the dose-response relationship developed earlier, and to determine the impact of temperature on germicidal efficiency.

Throughout the experimental study period, factors related to disinfection by the U.V. system were periodically evaluated. The system hydraulics were studied by measuring and evaluating velocity profiles across the exit plane of the lamp battery. This test was conducted to determine the flow distribution within the lamp battery. The cleaning efficiency of the wiper mechanism was evaluated by continuous monitoring of the quartz surface throughout the long term study, and by intentional shutdown and startup during a two-week period in November 1978. In this case, the wiper was turned off and the lamp battery quartz tubes were observed for surface fouling. Coliform kill efficiencies were measured with time.

Several studies were conducted to determine the impact of photoreactivation on system efficiency. These studies, for the most part, involved static light/dark bottle test procedures, and were conducted primarily during the months of June through August 1978, and February through April 1979. An alternate procedure, a dynamic test, was conducted directly in the chlorine contact chamber receiving the U.V. system effluent. This photoreactivation test was conducted periodically to complement the static bottle tests.

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ULTRAVIOLET SYSTEM MONITORING

The U.V. disinfection system was monitored with each sampling for power consumption, relative U.V. intensity, wiper and lamp operation, and flow rate. These same parameters were also monitored routinely during periods when sampling was not being conducted.

Power Consumption

The disinfection system operated on three phase current. The applied voltage was varied from 40% to 100% of the total voltage (480 volts). The line voltage and current were measured over each phase, and the power was then computed by the formula

$$\text{Watts} = (\text{Amps} \times \text{Volts})/(0.95 \times \sqrt{3}) \qquad (5\text{-}1)$$

where the power factor (0.95) was derived from the total energy consumption for a known time period.

Lamps Engaged

The 400 germicidal lamps were segmented into 6 banks and any combination of banks could be engaged at a given time. Pilot lights were originally installed with the system to monitor the operation of each lamp. However, in time, it became apparent that many of the pilot incandescent bulbs could be out while the U.V. lamps were still functioning, negating their effective use as a lamp monitor.

In practice, the determination of the number of lamps engaged involved measuring the line current across each lamp. This was a time consuming practice. Weekly or biweekly inventories of the number of lamps functioning were made and found adequate for monitoring purposes. A small number of lamps were monitored by light emitting diodes (L.E.D.) which also proved an effective procedure.

Wiper Action

Wiper action remained continuous throughout most of the study period. An automatic counter recorded the total number of wiper strokes, and at each sampling or monitoring sequence, the stroke rate, generally six strokes per hour, was noted.

Flow Rate

The flow through the U.V. chamber was measured with the V-notch weirs positioned at the end of the U.V. disinfection channel (see Figure 2). The weirs were calibrated by a series of dye and lithium tracer studies. Prior to May 4, 1978, the water level above the weir was measured manually at the time of sampling. Subsequently, a bubbler level sensor and continuous recorder were utilized to obtain a continuous record of the flow.

Relative U.V. Intensity

Ultraviolet intensity measurements (at 253.7 nm) were typically recorded during each sampling sequence. The field probe for the PWS Model GL100 U.V. intensity meter was mounted on a guide-rod such that when the probe was placed against a quartz tube, the sensor was 0.635 cm from the quartz surface. Only the first and last vertical lamp rows were monitored, since only these rows were accessible to the probe while the unit was submerged and operational.

Generally, ten lamps (of 20) in each of the two rows were measured for U.V. intensity and then an average intensity was computed. Note that these direct readings are considered relative values, and are not measures of actual U.V. intensity. The relative intensities were recorded with each sampling sequence to provide an indication of the quartz clarity and the lamp performance. The theoretical U.V. output at the quartz surface corresponding to the relative intensity index is presented in Figure 7. The observations presented on Figure 7 represent readings taken at various voltage settings. The theoretical intensity is based on a single lamp, and does not account for the compounding effects of several lamps in close proximity. Similarily, the probe does not account fully for the multi-lamp compounding effect, since the sensor is recessed 0.635 cm from the quartz surface and can only detect wavelengths entering in a straight line. The relative intensity measure was very useful in detecting a decline in lamp performance (output at 253.7 nm) caused by fouling of the quartz tubes or aging of the lamps.

SAMPLING

All sampling was conducted on a grab basis. Samples were drawn with a Wheaton sub-surface water sampler, which allowed a closed sterile container to be submerged at any prescribed depth in the water. The container could then be opened remotely and the sample drawn. Influent and effluent samples were each drawn within a 5 minute interval in any given sampling sequence. One liter glass bottles were used in all cases, each of which had been washed, rinsed with distilled water, and sterilized by autoclaving for thirty minutes at 121° C. Sample bottles used to contain irradiated effluent water were painted with heat resistant opaque black paint in order to eliminate any potential interference in bacterial density measurements from photoreactivation.

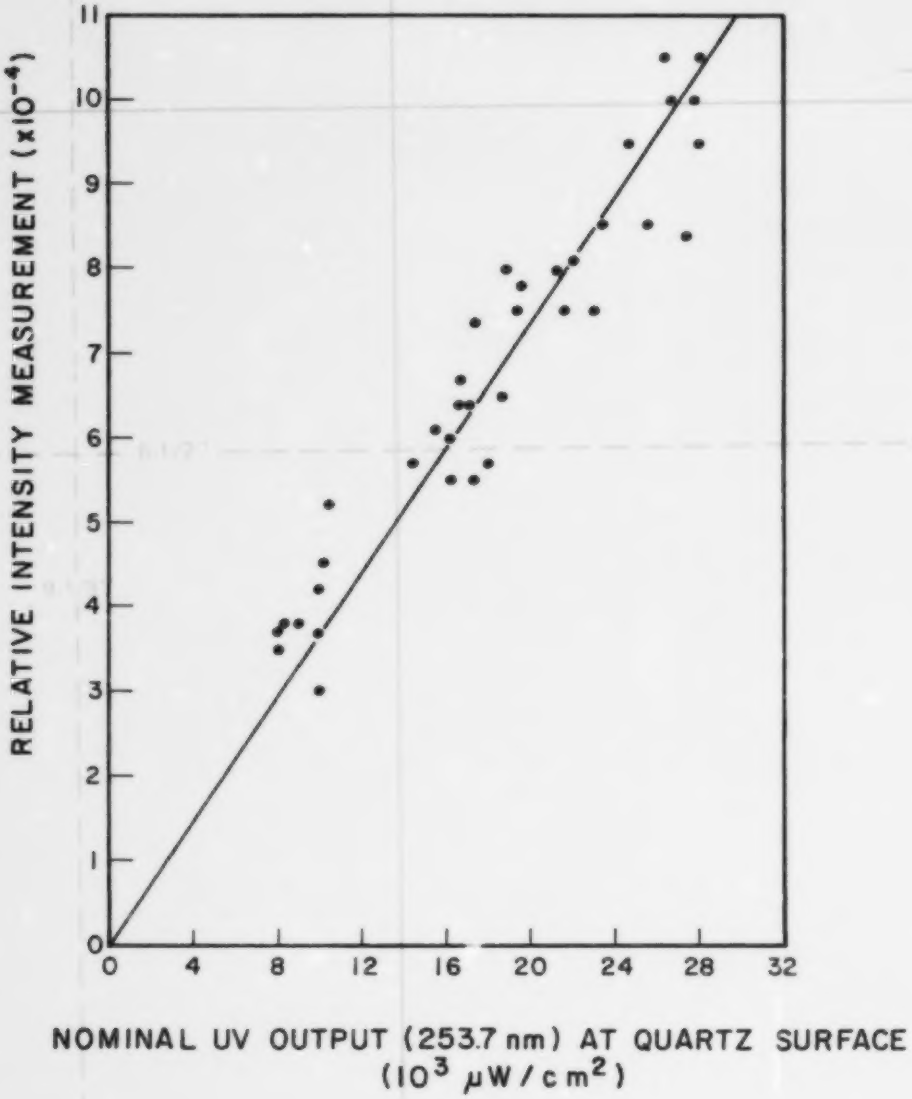

Figure 7. Calibration of relative intensity measurement to nominal ultraviolet intensity.

Influent samples were obtained from the influent channel at the discharge from the sluice gate (see Figure 2). The irradiated effluent samples were drawn at the center point of the lamp battery, approximately 30 cm from the last row of lamps.

Sampling sequences, which involved sampling the influent and effluent several times in one day at various operational settings (doses), were randomized to minimize bias from diurnal water quality variations. This was particularly the case during the July through August, 1978, and February through March 1979 sampling periods. As an example, the sampling in June consisted of eight operational modes, obtained by varying the flow between two settings, and by varying the applied voltages at 4 discrete settings. The number of lamps in operation was held constant. On a test day, samples were taken at each of the eight operating conditions, the sequence of which was randomized for each day. Eight replicate sequences were sampled for this particular set of conditions.

A second set of operating conditions was evaluated on a similar basis during the period of July and August, 1978. During the months of February, March, and April, 1979, three dose conditions were evaluated by varying the number of lamps engaged, or by changing the applied voltage. The dose conditions were set just prior to sampling, three times a day, three days a week. Again, as discussed above, the sequence of sampling was randomized each day. The remaining months of the experimental program were devoted to steady state monitoring and generally entailed sampling at a single dose level. The irradiated effluents were typically sampled in replicate during this period.

ANALYTICAL SCHEDULES AND PROCEDURES

Sampling and monitoring of the system was conducted routinely, typically two to four days per week and several times (two to eight) within the day. It should be noted that the system itself was operated continuously and was shut down only during periods of maintenance (or repair) or when the experimental program called for shutdown of portions of the unit (i.e. lamp banks).

Analytical Schedules

Table 3 presents the analytical schedules used to characterize the wastewater during various phases of the experimental program. The number of analyses conducted per sample was highest during the initial phase (March-May 1978). During this period total and filtered components were evaluated for a number of parameters, on both the influent and effluent. This schedule was reduced in the first part of the June through August

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TABLE 3

ANALYTICAL SCHEDULE FOR ULTRAVIOLET DISINFECTION EXPERIMENTAL PROGRAM

Parameter		Test Period March - May 1978	 June - August 1978
Samplings (% of Total)		15%	35%
Total Coliform		I/E	I/E
Fecal Coliform		I/E	I/E
Fecal Streptococcus		-	-
U.V. Absorbance	Total	I/E	I/E
	Filtered	I/E	I/E
COD	Total	I/E	I (E-June)
	Filtered	I/E	I (E-June)
TOC	Total	I/E (60%)	-
	Filtered	I/E (60%)	-
Color	Filtered	I/E	I/E - June
Suspended Solids		I/E	I (E - June)
Turbidity		I/E	I (E - June)
pH		I/E	I (E - June)
Temperature		I/E	I
TKN	Total	I/E (50%)	-
	Filtered	I/E (50%)	I (E - June)
NH_3-N		I/E (50%)	I (E - June)
NO_2-N		I/E (50%)	I (E - June)
NO_3-N		I/E (50%)	I (E - June)
Photoreactivation		Special Studies	Routine

I = Influent
E = Effluent
(%) = Frequency

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TABLE 3
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ANALYTICAL SCHEDULE FOR ULTRAVIOLET DISINFECTION EXPERIMENTAL PROGRAM

Parameter		Test Period September 1978 - January 1979	Test Period February - April 1979
Samplings (% of Total)		30%	20%
Total Coliform		I/E	I/E
Fecal Coliform		I/E	I/E
Fecal Streptococcus		I/E (25%)	I/E (25%)
U.V. Absorbance	Total	I/E	I/E
	Filtered	I/E (25%)	I/E (25%)
COD	Total	I (50%) E (20%)	I(15%)
	Filtered	I (100%) E (20%)	I (75%) E (15%)
TOC	Total	-	-
	Filtered	-	-
Color	Filtered	-	-
Suspended Solids		I	I
Turbidity		I	I
pH		I	I
Temperature		I	I
TKN	Total	-	-
	Filtered	I/E (20%)	I/E (15%)
NH_3-N		I/E (15%)	I/E (15%)
NO_2-N		I/E (10%)	I/E (15%)
NO_3-N		I/E (10%)	I/E (15%)
Photoreactivation		Special Studies	Routine

I = Influent
E = Effluent
(%) = Frequency

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sampling period, whereby the TOC and total TKN analyses were not performed. Once it was confirmed that there was no significant difference between the influent and effluent wastewater quality (aside from the bacterial characteristics), the analytical schedule was reduced to analysis of only the influent for the major wastewater quality parameters. The effluent samples were analyzed only for coliform densities and U.V. absorbance.

During the latter two phases, the analytical schedule gave primary emphasis to coliform density, U.V. absorbance, COD, SS, turbidity, and temperature. The nitrogen series was determined intermittently. Fecal streptococal density determinations were also added to the schedule for these study phases.

Table 3 also shows, for point of reference, the approximate distribution of samplings for the various sampling periods. There were a total of 375 samplings (a single sampling entailed drawing an influent and effluent sample), excluding photoreactivation sampling. During the March-May and the September-January periods, photoreactivation was evaluated on selected days as a part of special studies. In the remaining two periods, photoreactivation analyses were conducted on a routine basis.

Analytical Procedures

Procedures used in the analysis for the various wastewater and bacterial parameters listed on Table 3 followed those described by Standard Methods (30), and/or the USEPA (31).

Total Coliform, Fecal Coliform, Fecal Streptococcus--

Total and fecal coliform densities were determined by the multiple tube fermentation technique. Originally, five dilutions with five tubes per dilution were set in lactose broth for the presumptive test. Once experience was gained as to the density levels, four dilutions were used routinely. These innoculated tubes were incubated at 35 ± 0.5°C for 24 hours ± 2 hours. At 24 hours, all samples which gave a positive gas formation reading were recorded, gently mixed, and transferred (with a sterile platinum 3 mm diameter loop) into prepared tubes of brilliant green lactose bile broth and EC medium for confirmed tests of total and fecal coliforms, respectively.

Those lactose tubes (presumptive test) that were negative after 24 hours were returned to the incubator until a total incubation time of 48 ± 3 hours elapsed. Any positive tubes after 48 hours were then transferred for the confirmed tests.

The cultures transferred into brilliant green lactose bile broth for the confirmed test of total coliform were incubated at

35 ± 0.5°C for 48 ± 3 hours. The tubes were checked for the formation of gas (positive test) at 24 hours and at 48 hours.

The cultures transferred into the E.C. medium for the confirmed test of fecal coliform were incubated in a water bath at 44.5 ± 0.2°C for 24 ± 2 hours and then checked for the formation of gas.

Fecal streptococcus were measured using the multiple tube technique following the presumptive and confirmed test procedures as outlined in *Standard Methods*. Four dilutions, with five tubes per dilution, were analyzed. Sterile wooden applicators were used to transfer cultures.

The air incubator, a Fisher Isotemp Model 503, was continually maintained at 35° C. The temperature was recorded each day, and adjusted whenever necessary. The water bath, Fisher Blue M Magni Whirl constant temperature bath, was maintained at 44.5°C. The temperature was recorded with each use and adjusted when necessary. The water level in the bath was frequently checked and maintained at a level sufficient to submerge the media held in the tubes.

All media were prepared in accordance with procedures outlined in *Standard Methods*. Distilled water used for preparation of the media was periodically checked for quality, particularly with regard to trace metals contamination. Each medium was dispensed to disposable glass culture tubes, which were then prepared and autoclaved for 15 minutes at 121° C, with a 15 minute cooling cycle. The medium pH was measured before and after sterilization as a check on materials quality. Any media which were not used within two weeks were discarded.

All culture tubes (with media) and sample bottles were prepared at the HydroQual Laboratories and transported to the Northwest Bergen County facility, where all samplings and innoculations were conducted. Innoculations were carried out as soon as possible after the sample was drawn. In the case where several samples were drawn at one time, samples were stored at 4°C until the innoculation could be conducted. Storage was typically less than one hour. Incubation of innoculated tubes was conducted on-site at the NW Bergen facility.

Filtrations--

Filtrations necessary for estimates of soluble components were accomplished with Gelman GF/B glass fiber filters under 20-25 inches vacuum.

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Ultraviolet Absorbance--

Absorbance of ultraviolet energy at the wavelength 253.7 nm was measured with 1 cm pathlength quartz cells. A Beckman ACTA II spectrophotometer was utilized with a deuterium lamp as the light source. Direct readout is absorbance units per centimeter, or a.u./cm. This is converted to a percent transmittance by the expression,

$$\% \ T = 100 \ (10^{-\text{a.u./cm}}) \qquad (5\text{-}2)$$

The absorbance coefficient, which is the term generally referred to in this report, is computed as

$$k = 2.3 \ (\text{a.u./cm}) \qquad (5\text{-}3)$$

Chemical Oxygen Demand (COD)--

The COD analyses were performed by the modified rapid procedure, as developed by Jeris (32). This procedure was tested initially against the reflux procedure in Standard Methods. The results indicated no significant difference (5% confidence limits) between the two procedures for routine analysis of the NW Bergen plant effluent.

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Total Organic Carbon (TOC)--

TOC was measured by a Beckman Model 915 Total Organic Carbon analyzer.

Color--

Color was determined at a wavelength of 465 nm, utilizing a Beckman Spec 20 spectrophotometer. Platinum-cobalt was used to develop the standard curve, as described in Standard Methods.

Suspended Solids--

Suspended solids were determined with pre-washed Gelman GF/B glass fiber pads. The residue was dried at 103°C for a minimum period of one hour.

Turbidity--

Turbidity was measured on a Hach Turbidimeter, Model 1860, which was calibrated at each use with a 10 nephelometric turbidity unit (NTU) standard prepared from a stock Formazin suspension.

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pH--

The pH was determined with an Acumet Model 150 pH meter which was calibrated with a stock pH 7.0 buffer solution with each use.

Temperature--

Temperatures were measured using a general laboratory thermometer registering from -10°C to 270°C.

Total Kjeldahl Nitrogen, Ammonia Nitrogen, Nitrite Nitrogen, Nitrate Nitrogen--

Automated procedures were utilized to determine the various components of the nitrogen series. Digestion of the TKN was accomplished with a Technicon BD-40 block digestor. A Technicon Autoanalyzer II was utilized for the ammonia analysis by the phenate method. Nitrate and nitrite analyses were performed with a Technicon Autoanalyzer I using the modified brucine sulfate procedure for nitrate, and the modified diazotization method for nitrite.

Photoreactivation--

Photoreactivation tests were conducted throughout the field study. The evaluations involved two procedures, the static bottle test and the dynamic flow through test.

Static Test - The static test procedure for photoreactivation involved splitting an irradiated effluent sample into so-called "light" and "dark" bottles. The light bottles were transparent to visible light, while the dark bottles were opaque. These bottles were immersed in a water bath of constant temperature equal to the ambient wastewater temperature, or, more typically, in the contact chamber itself. The bottles were exposed to sunlight for selected periods of time, and samples were then drawn and analyzed for coliform density. The time of exposure was typically one hour. The results of the light and dark bottle tests were then compared to the coliform density of the same sample, which had been measured immediately after U.V. irradiation.

Dynamic Tests - Dynamic photoreactivation tests were conducted in the contact channel to approximate stream flow conditions and to determine if daylight exposure conditions in the study channel were conducive to photoreactivation. The test involved imposing steady state conditions on the disinfection system (flow and operational mode) several hours prior to testing. The tests were conducted at relatively low flows to obtain detention times in the channel in the order of one to three hours. Chlorination was discontinued at least 16 hours prior to testing. A chlorine residual was maintained in the total plant effluent by increasing the chlorine dose to the active chlorine contact channel.

Samples were drawn from the channel (typically at the V-notch weir) at selected time intervals after the initial irradiated sample was taken following the U.V. unit. These results were compared, and were also compared to the static test results, which evaluated photoreactivation at a fixed exposure position.

SECTION 6

ULTRAVIOLET DOSE

Pathogenic bacteria, viruses, fungi, and other microorganisms are subject to destruction from ultraviolet irradiation provided the energy is absorbed by the vital genetic material of the cells. Given a population of microorganisms, it follows that the probability of their being destroyed is enhanced when the U.V. intensity (or the rate at which the energy is delivered) is increased, and/or when the time to which the organisms are exposed to ultraviolet radiation is increased. The product of these two factors, intensity and exposure time, has historically been referred to as the ultraviolet dose:

$$\text{U.V. Dose } (\mu\text{W-sec/cm}^2) = I \times t \qquad (6\text{-}1)$$

where:

I = U.V. Intensity (μW/cm^2)

t = exposure time (seconds)

Numerous U.V. investigations, ranging from laboratory scale analyses of pure cultures, to field scale evaluations of naturally occurring homogenous bacterial and viral populations, have typically resulted in response relationships as a function of the applied U.V. dose. The generation of dose-response curves is certainly a rational approach, yielding a definitive cause/effect relationship.

Such dose-response relationships should logically serve as the basis for the design of a U.V. system. Given a desired response, i.e., a specific effluent bacterial density requirement, a U.V. dose level can be defined. This dosage can, in turn, serve to define the physical design of the proposed U.V. system, since the expression contains the parameters which relate directly to system design: intensity, which is a function of lamp size and number, U.V. output rating, water quality, and lamp placement; and exposure time, which is a function of the sizing of the lamp battery, and the hydraulic characteristics of the unit.

The development of a system design based on an accurately determined dose-response expression implies that for a given response requirement, a matrix of equipment specifications (i.e., number of lamps, spacing, etc.) exists which will deliver the same dose. Simplistically, this means that for a given water condition, a "thin film" system (closely spaced lamps) and a "thick film" system (widely spaced lamps) can be designed to deliver the same dose in order to achieve the same response.

A comparative evaluation of U.V. disinfection studies reported in the literature clearly demonstrates that there are significant dissimilarities in the methods of measuring and the manner of reporting U.V. dose. The cause of these apparent discrepencies lies in the lack of a uniform procedure, which is accepted as a standard method, to measure, or report the applied dose. Without this, it is difficult to establish or report a rational and uniform procedure for the design of U.V. disinfection systems.

Although not in the original scope of work for this project, it became apparent, as the program progressed, that a uniform procedure would need to be developed to define the U.V. dose. This was necessary to develop effective dose-response curves and to provide a basis for design. The approach taken was to retain the concept of dose as the product of intensity and exposure time. The derivation of these two variables, however, was to reflect accurately the physical and water quality aspects of system design; and the parameters were to be measured, or computed, in a way which would be consistent with alternative system configurations. Thus, the method would be rationally based and uniformly applicable to various system designs. The following discussions present the methods developed and used, within the context of this report, to compute the applied U.V. dose.

EXPOSURE TIME

Exposure time defines the period of time, typically in seconds, to which a water sample or a population of microorganisms undergo irradiation. The exposure time in dynamic or flow-through, systems is assumed to be equivalent to the mean cell residence time, or simply, the average hydraulic detention time.

Theoretically, the exposure time may be computed as:

$$t_e = \frac{V_v}{Q} \qquad (6\text{-}2)$$

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where:

t_e = Exposure time,

V_v = Void volume, which is the total reactor volume minus the displacement volume of materials contained in the reactor (e.g., U.V. lamp and quartz enclosures),

Q = Flow.

Often, however, the actual exposure time will deviate from theoretical due to the hydraulic characteristics of a specific system design. As an example, if short circuiting is known to occur within a system, the actual time may be less than theoretically expected.

Procedures exist which serve to characterize the hydraulics of a system and thus provide a direct estimation of the exposure time. One such procedure involves tracer analyses, whereby a conservative substance (examples are rhodamine dye, lithium salt, radioactive tracer, etc.) is injected into the influent stream, either continuously at a known rate, or as an impulse of known mass. Measure of this material as it exits the system with time allows an accurate measure of exposure time as a function of the flow rate.

Use of the tracer analysis technique was not considered for the NW Bergen project. Expected exposure times were in the order of 1 to 4 seconds and, given the size of the system, an effective and practicable tracer experiment could not be designed which would have acceptable precision at such low detention times. Alternatively, velocity profiles across the exit face of the lamp battery were determined at two flow conditions using a Gurley velocity meter. The results of this analysis are shown on Figure 8. The data indicated little evidence of short circuiting. The velocities (particularly in the typical flow range of 0.17 to 0.26 m^3/sec) were relatively consistent across the system. At 0.27 m^3/sec, the average measured velocity was 27.1 cm/sec with a standard deviation of 3.2 cm/sec. For a flow of 0.1 m^3/sec, the mean velocity was 3.23 cm/sec, with a standard deviation of 1.1 cm/sec.

Since the exposure time could not be accurately or precisely measured for the system utilized at NW Bergen (at least in a manner which would be within the practicable scope of work), the theoretical calculation was used to estimate the exposure time at various flows. This was judged to be a reasonable estimate since no unusual hydraulic characteristics were encountered which would cause any significant deviation of the actual exposure time from the theoretical exposure time. The void volume (subtracting the displacement volume of the 400 quartz

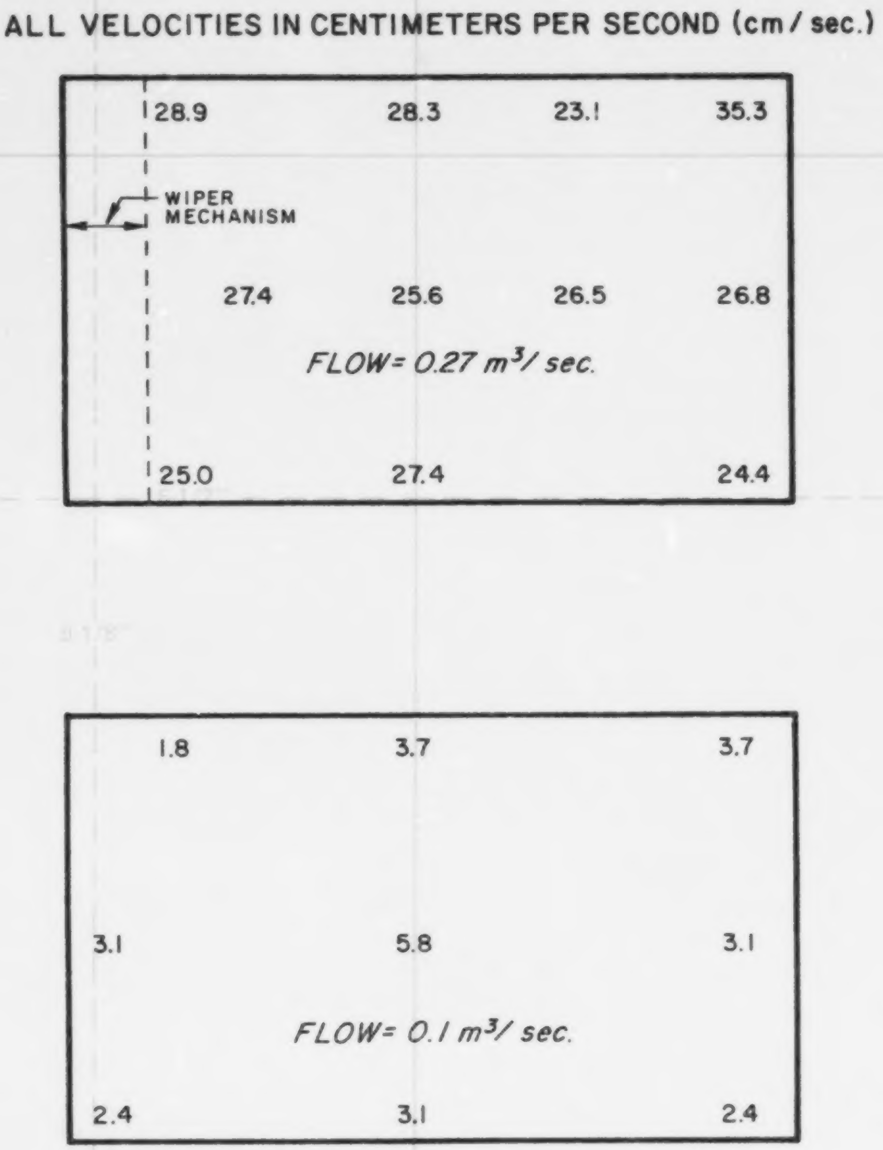
ALL VELOCITIES IN CENTIMETERS PER SECOND (cm / sec.)
28.9
28.3
23.1
35.3
WIPER MECHANISM
27.4
25.6
26.5
26.8
FLOW= 0.27 m³/ sec.
25.0
27.4
24.4
1.8
3.7
3.7
3.1
5.8
3.1
FLOW= 0.1 m³/ sec.
2.4
3.1
2.4

Figure 8. Velocity distributions across exit plane of U.V. disinfection unit.

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enclosures) of the lamp battery was determined to be 0.49 m^3. In instances where a portion of the system (i.e., banks of lamps) was shutdown, the exposure time was computed from the void volume attributed to the lamps in operation. Thus,

$$t_e = \frac{\text{Total Void Volume x [Lamps in Operation/400]}}{Q} \qquad (6\text{-}3)$$

ULTRAVIOLET INTENSITY

Ultraviolet intensity expresses the rate at which energy is being delivered or transmitted to a particular surface. Since the maximum output (typically 80% of U.V. output) for low pressure mercury arc lamps is at the wavelength 253.7 nm, intensity measurements are normally made at this wavelength. This intensity, when multiplied by the time the surface is exposed, yields the U.V. dose in disinfection applications.

A major problem in deriving a reasonable estimate of dose lies in the inability to accurately measure the average U.V. intensity within a system. This has been compounded by the newer system designs in which bundles of lamps are submerged in the waters to be treated. In the simpler laboratory studies, a single lamp was utilized, typically suspended over a fixed sample. The intensity could be accurately measured by simply setting the U.V. intensity probe (properly calibrated) at an equal distance from the source.

The earlier dynamic systems (such as the Kelly-Purdy design) were similar in the sense that the energy was directed to a plane surface. A number of lamps would be suspended above a shallow tray of continually flowing water. Reflectors were placed above the lamps to redirect light back to the water surface. The intensity was highest at the water surface and decreased with the depth of the liquid (5-10 cm) due to absorption of the radiant energy by the liquid medium. This attenuation is best described by Beer's Law,

$$I = I_o e^{-kd} \qquad (6\text{-}4)$$

where:

I = intensity at distance d ($\mu W/cm^2$)

I_o = incident intensity ($\mu W/cm^2$)

d = distance from the point of incidence (cm)

k = absorbance coefficient (cm^{-1})

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The average intensity can be computed by integrating the above function between the surface and the depth of interest, and dividing by the depth. This yields the expression,

$$I_{avg} = I_o\left(\frac{1-e^{-kd}}{kd}\right) \qquad (6\text{-}5)$$

The absorbance coefficient, in the above application, can be obtained experimentally by measuring the intensity at various depths. The coefficient is then described by the slope of a log intensity versus depth relationship.

Measurement of the absorbance coefficient, intensity, and exposure time are all relatively practicable procedures for the shallow tray design, and should yield a fairly accurate estimate of the ultraviolet dose. Since the energy is approaching from a single direction and onto a plane surface, the measurement of intensity should be reasonably accurate. Also, since the exposed surface remains constant with depth, intensity attenuation is due to absorption alone, and not to dissipation (as would occur if the exposure area was continually expanding with depth).

The increasing refinement of U.V. system designs has led to the use of exposure chambers in which the lamps are fully submerged in the process waters. Mechanical and chemical cleaning mechanisms have been incorporated to prevent fouling of the quartz surfaces (this had been the primary reason for not submerging the lamps, particularly in low grade waters). The major advantage which is gained by submerging the lamps is that greater energy utilization is achieved, since the emission about the entire circumference of the lamps is directed into the water medium. The design, however, prevents the direct measurement of U.V. intensity at any point within the lamp battery. The U.V. energy is not being transmitted in a single direction nor is it transmitted to a plane surface (as was the case with the shallow tray design). Energy transmission is directed outward from the arc source along a 360° circumference; thus as the distance from the source increases, the intensity will attenuate due to energy absorption by the liquid medium and due to dissipation, or dilution, of the energy as the exposure area increases. Additionally, any single point will be affected by all surrounding lamps. U.V. sensors (at least present designs) are unable to accurately measure or account for this compounding effect.

The lack of an effective and practical experimental procedure to directly measure intensity has led to alternative methods for estimating the average intensity within a submerged multilamp exposure chamber. The subsequent discussions detail the procedure which was used to estimate the average U.V.

intensity in the lamp battery system used for the Northwest Bergen project.

Determination of Average Ultraviolet Intensity

The nominal intensity at any distance from the lamp source can be determined directly from the lamp design and U.V. output rating. The specifications of the lamps used in this study (as provided by the equipment manufacturer) are as follows:

Lamp Model,	85-PWS-60
Nominal Power,	85 W
Lamp Current,	425 mA
Nominal U.V. Output at 253.7 nm,	30 W
Lamp length	152.4 cm
Arc length	142 cm

Each lamp was enclosed in a quartz tube which had a nominal outer diameter of 2.3 cm.

Incident Intensity--

The incident intensity, i.e., the intensity at the quartz surface before entry into the liquid medium, is computed as a function of the U.V. output at 253.7 nm and the surface area of the quartz enclosure. This assumes the lamp arc operates effectively as a line source, which is a reasonable assumption for the long tubular lamp designs. Other researchers have suggested that the arc be considered a series of point sources, with emission of energy from each point extending outward in the form of a spherical shell. This is a considerably more complicated approach; for purposes of this report, it is felt that the line source assumption more than adequately describes the emission of U.V. from the lamp.

The surface area of each quartz tube was 1000 cm^2 for the NW Bergen system. Thus, at the rated germicidal output of 30 Watts and assuming a 10% absorption of U.V. through the quartz, the nominal incident intensity at the quartz surface was estimated to be 27,000 $\mu W/cm^2$.

Intensity Attenuation--

The U.V. intensity emitted by a lamp (assuming it to be a line source) will attenuate as the distance from the energy source increases. This attenuation occurs via two mechanisms, dissipation and absorption.

Dissipation - The first mechanism is simply the dissipation, or dilution of the intensity. As the distance from the energy source increases, the surface area over which the constant output of photons is projected also increases. Thus, there are fewer photons striking each square centimeter of surface area as the distance from the source increases. This dissipation is described by the ratio of surface areas, which reduces to the ratio of the radii,

$$\frac{I}{I_o} = \frac{r}{r+x} \qquad (6-6)$$

where:

r = radius of the quartz enclosure (cm)

x = distance from the surface of the quartz (cm)

This analysis is confirmed by data presented by General Electric (33) for a G64T6 germicidal lamp. The rated U.V. output of this lamp is 18 W, and the incident intensity is computed to be 20450 $\mu W/cm^2$, based on the dimensions of the lamp. The intensity data reported by General Electric at several points distant from the lamp are presented on Figure 9. The computed relationship of intensity with distance, as described by expression (6-6), is also presented on Figure 9. As shown, there is good agreement with the observed data.

Energy Absorption - The second attenuation mechanism relates to the absorptive properties of the medium through which the energy is transmitted. The absorption of ultraviolet radiation in a wastewater is commonly defined by the absorbance coefficient, which is a measure of the unit absorbance of a beam of light passing through a known liquid depth. This is Beer's Law, which was presented in Equation (6-4).

It should be noted that recent work indicates that measurement of absorption by a beam attenuation spectrophotometer (which operates on the principle of Beer's Law, and which was used for this study) may result in an underestimation of the amount of U.V. energy available for disinfection purposes. Miller and Zepp (34), in their studies of photolysis in natural waters, suggested that significant underestimates of photolysis rates result when beam attenuation coefficients of turbid water bodies are employed to compute the effects of light attenuation. The enhanced photolysis rates which were observed in turbid waters were attributed to the increased diffuseness of light caused by scattering. Thus, in future evaluations of U.V. disinfection, an obvious refinement in characterizing the U.V. absorbance of a wastewater would be to differentiate between the specific, or true, absorbance, and scattered light.

The attenuation factors, dissipation and absorption of energy, combine to define the intensity at any point relative to

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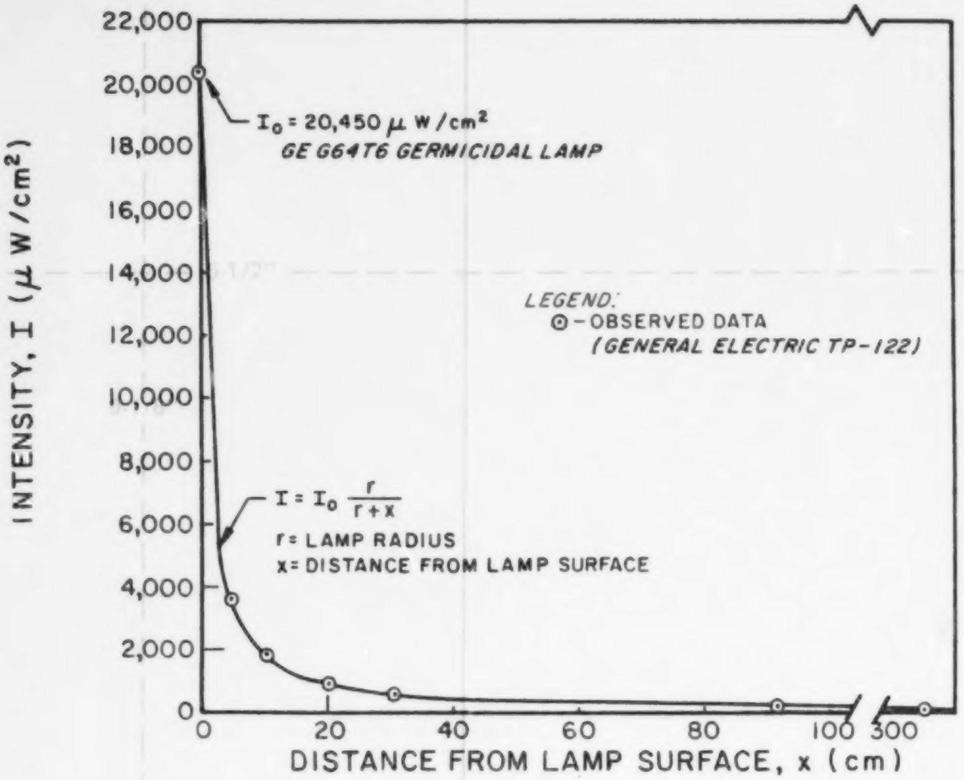

Figure 9. U.V. intensity attenuation with distance.

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the nominal incident intensity of a lamp. Thus, the intensity at any point from a single lamp can be defined as,

$$I = I_o \frac{r}{r+x} e^{-kx} \qquad (6\text{-}7)$$

Figure 10 presents solutions to the above expression for a single lamp, displaying the relative intensity with distance at several absorbance coefficient values. In multilamp ultraviolet disinfection systems, several lamps are placed in an array and the intensities described by Equation (6-7) for each lamp become additive.

Computation of Average Intensity--

Summarizing to this point, the computation of the average intensity of a particular system will be dependent upon the lamp spacing (which influences x in Equation 6-7), lamp rating (I_o), lamp dimensions (r), and the absorbance characteristics of the medium (k). The approach taken to determine the average intensity for the NW Bergen system was to use Equation (6-7) to construct isointensity lines on a cross-sectional plane of the lamp battery. A planimeter was then used to integrate the isolines and to compute the average isointensity line. This procedure was followed to provide solutions at various absorbance coefficient values for the lamp placement design at NW Bergen. Subsequent analyses were then performed to develop similar solutions at alternate lamp spacings. The following discussions describe the procedure specific to the N.W. Bergen system.

The system, as shown in Figure 6, was composed of 400 lamps in a 20 x 20 array. Each lamp was enclosed in a quartz tube with an outer diameter of 2.3 cm. A scale drawing of the lamp battery cross-section was constructed. The four center lamps of the battery were then selected, and a square was drawn between the four lamp centers, as shown on Figure 11. The isointensity lines were then constructed for this square, based on the additive influences from the surrounding lamps. By symmetry, it was assumed that the average isointensity line computed for this square was representative of the average intensity for the total system.

Again by symmetry, it was necessary to analyze only one sector (octant) of the selected square. This sector is shown in Figure 11. Approximately 30 points were then located uniformly in the sector. The distances from the center point of each lamp in the battery to each of the 30 points in the sector less the radius r were recorded. These values were noted as distance x. Additionally, if a vector from a lamp center to a point passed through a lamp, or lamps, the total distance through the lamps

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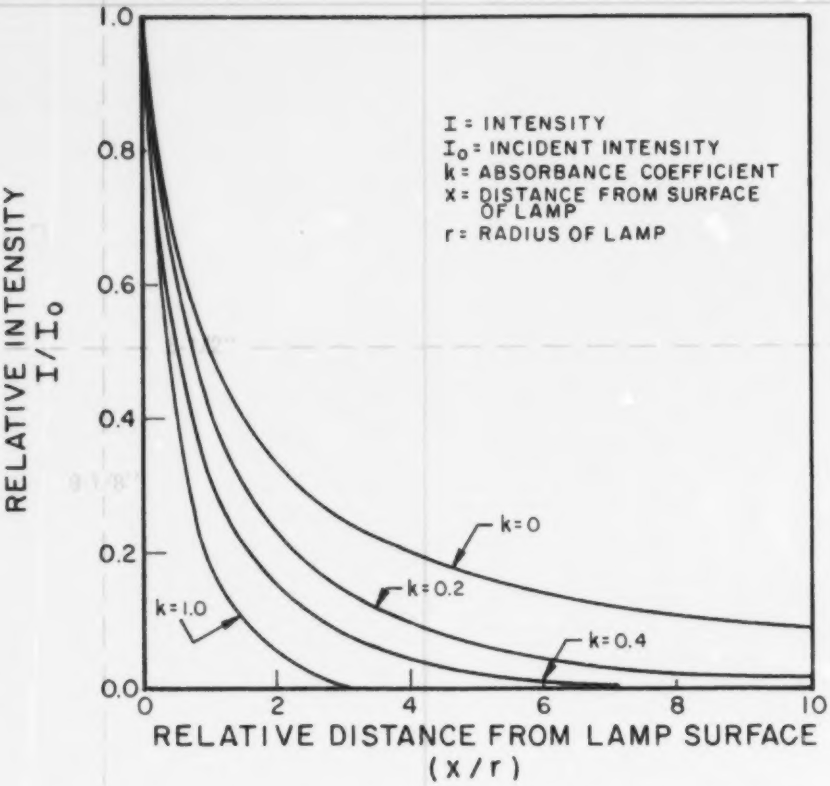

Figure 10. Attenuation of intensity with distance from a single source.

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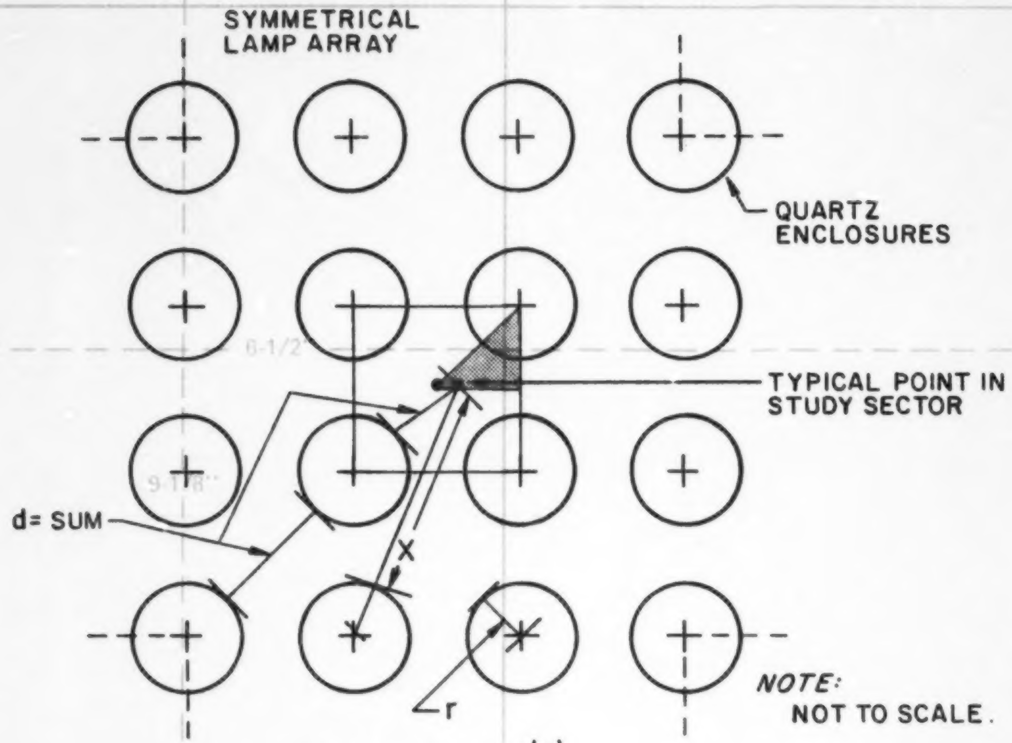
SYMMETRICAL LAMP ARRAY
QUARTZ ENCLOSURES
TYPICAL POINT IN STUDY SECTOR
d= SUM
x
r
NOTE:
NOT TO SCALE.

$$I = I_0 \frac{r}{r+x} e^{-kd}$$

Figure 11. Computation of intensities.

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was noted and subtracted from distance x. This length was recorded as distance d and represented the travel distance through the wastewater medium only.

The intensity from each lamp was then computed for each point by the relationship

$$I = I_o \frac{r}{r+x} e^{-kd} \qquad (6\text{-}8)$$

where x and d are the distances defined above. The value r is the radius of the quartz enclosure, which in this case was 1.15 cm. I_o is the incident intensity at each quartz surface. For convenience the incident intensity at each lamp surface, I_o, was set to 1.0 such that the computed intensities would all be relative to the incident intensity. The intensities were computed for several values of the absorbance coefficient, k.

The assumption inherent to the above calculation is that the lamps and quartz enclosures are transparent to exterior sources of ultraviolet energy. That is, for the distance traveled through the quartz enclosures, the absorbance is equal to zero. This is not entirely correct; lamp manufacturers suggest a loss of 10 to 15%. This was not accounted for in this analysis for the sake of simplicity. Tests for sensitivity indicated that in low grade waters with an absorbance coefficient greater than 0.1 cm^{-1}, the absorbance attenuation in the liquid medium far outweighs the absorbance attenuation through a lamp. Note, however, that the incident intensity calculation for the lamp and quartz enclosure does account for a 10% loss.

The intensities from each lamp at each point were then summed to provide the total relative intensity at each point in the sector. These same values were then mirrored in the remaining sectors of the square and the isointensity lines were determined for the square at the various absorbance coefficient levels. An example is displayed in Figure 12, which displays the isointensity lines for an absorbance coefficient of 0.4 cm^{-1} (which was typical for the NW Bergen study) and the lamp spacing shown on Figure 6. The figure considers only a four by four array of lamps. The computed mean isointensity line is dashed. Note that the highest intensities occur next to a single quartz surface, while the lowest intensity occurs at a point equidistant from the four lamps. The average intensity line was found to meet at a point midway of the minimum distance between two quartz surfaces. Since this point is symmetrical and easily located, the influence of additional lamps (and of varying lamp spacings and absorbance coefficients) on the average intensity can be readily determined.

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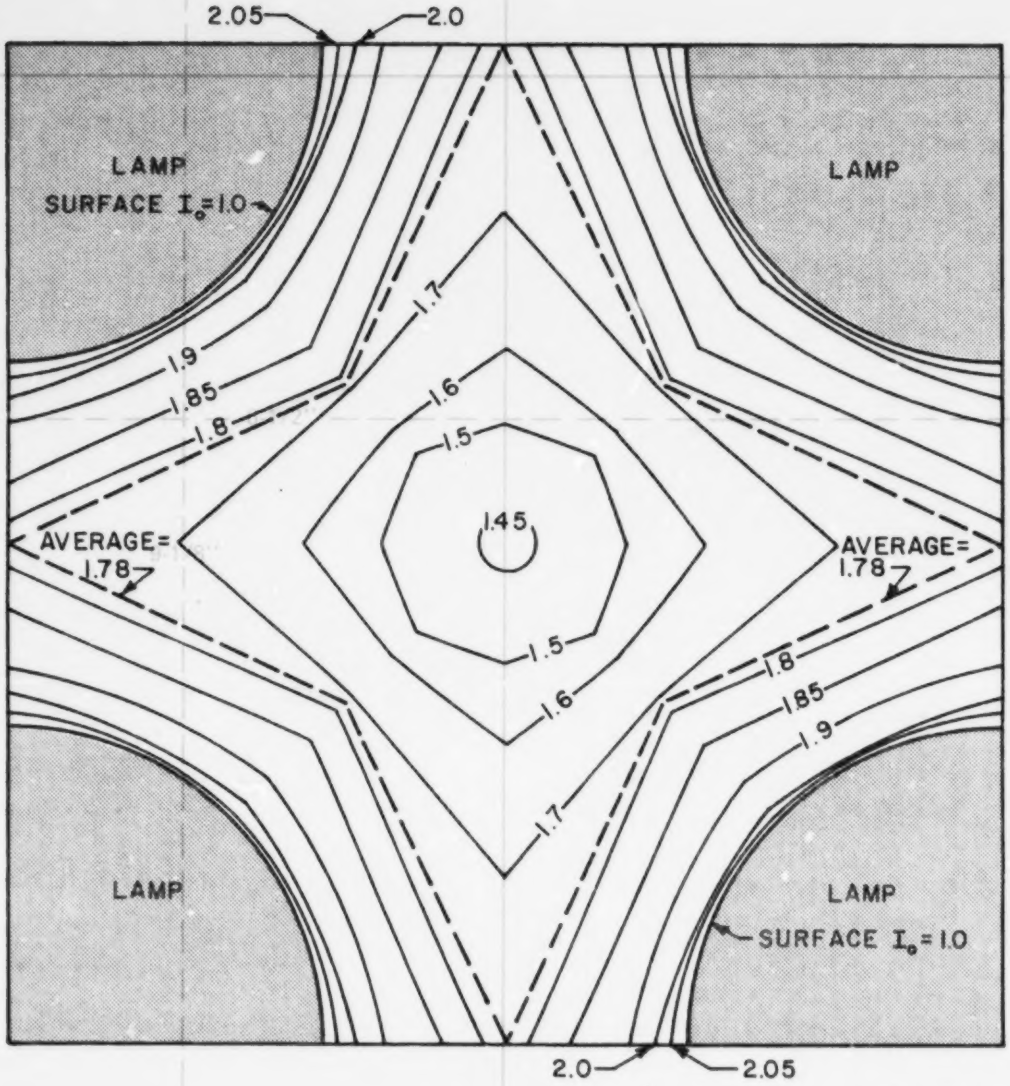

Figure 12. Example of computed isointensity lines in lamp quadrant.

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Returning to the example shown on Figure 12, the term compounding factor, F, is introduced. It is defined simply as the ratio of the average intensity and the computed incident intensity at the quartz surface. Thus for the case shown on Figure 12, F is equal to 1.78.

Figure 13 displays the impact of increasing the size of the lamp arrays. The relationships are for an array with a lamp centerline spacing of 3.55 cm, as was used for the NW Bergen system. The important point to consider from the analysis shown on Figure 13 is that at absorbances greater than 0.3 cm^{-1} there is minimal influence on the selected sector from lamps more than two rows out. Thus the compounding factor, F, which is computed for the area bounded by four lamps, should yield a good representation of the average intensity of the total system, particularly for systems with more than 100 lamps. Boundary effects (i.e., at the outer rows where a sector is not completely surrounded by lamps) were found to have little impact on the average intensity calculation. When the lamp spacing is increased, even fewer lamps will impact on the relative intensity within a selected sector. This logically follows from the increased absorbance and dissipation of the intensity with increased distance.

If the PWS system used at NW Bergen is considered, the analysis on Figure 13 indicates that the compounding factor, F, is 2.1 for $k = 0.4$ cm^{-1}. The computed incident intensity at full lamp power was determined to be 27,000 μW/cm^2 for this system; thus the average intensity of the system is 56,700 μW/cm^2 (2.1 x 27,000).

COMPUTATION OF THE APPLIED ULTRAVIOLET DOSE

Figure 14 presents solutions which relate the compounding factor, F, to lamp spacing at various absorbance coefficients, and alternately, F to the absorbance coefficient at various lamp spacings. The spacing in this case is defined as the shortest distance between any two quartz surfaces. The analysis also assumes that the quartz enclosures have a 2.3 cm diameter, and the lamps are in a symmetrical array, similar to that shown on Figure 6. If I_o is known, these two solutions can be used to determine what the average intensity is within a system at various lamp spacing and water quality conditions. Knowledge of the exposure time then allows computation of the ultraviolet dose.

The procedure which was utilized to determine the applied dose for the ultraviolet disinfection unit at the NW Bergen plant is presented graphically on Figure 15. These solutions apply only to this system. Other solutions would need to be developed for units of alternative configurations.

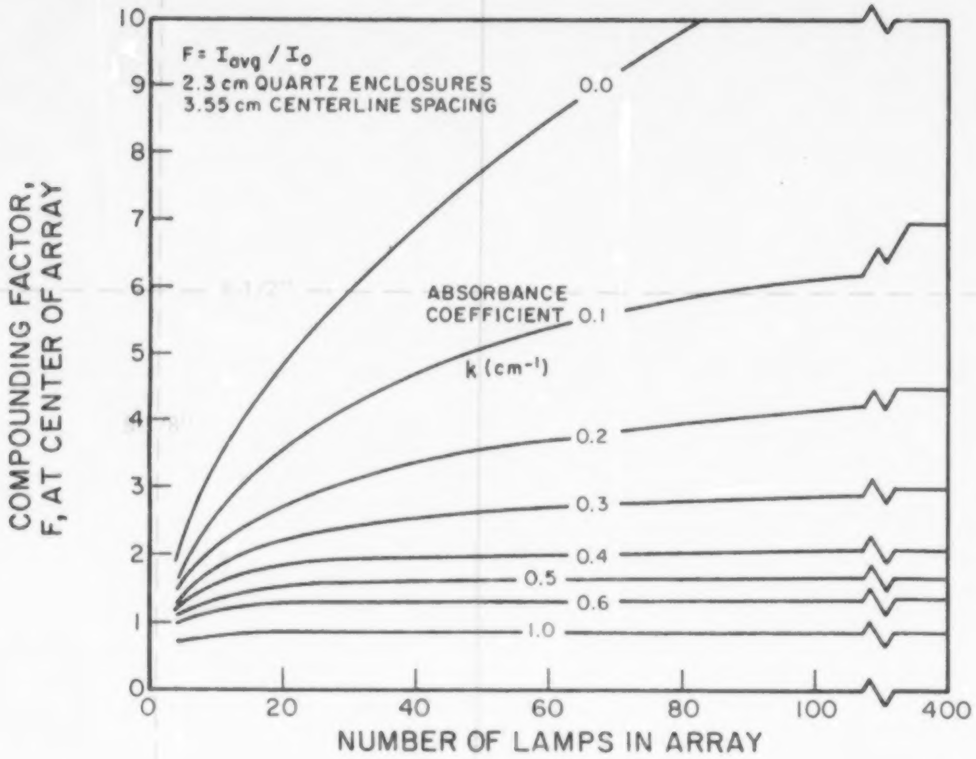

Figure 13. Impact of lamp array size on computed compounding factor.

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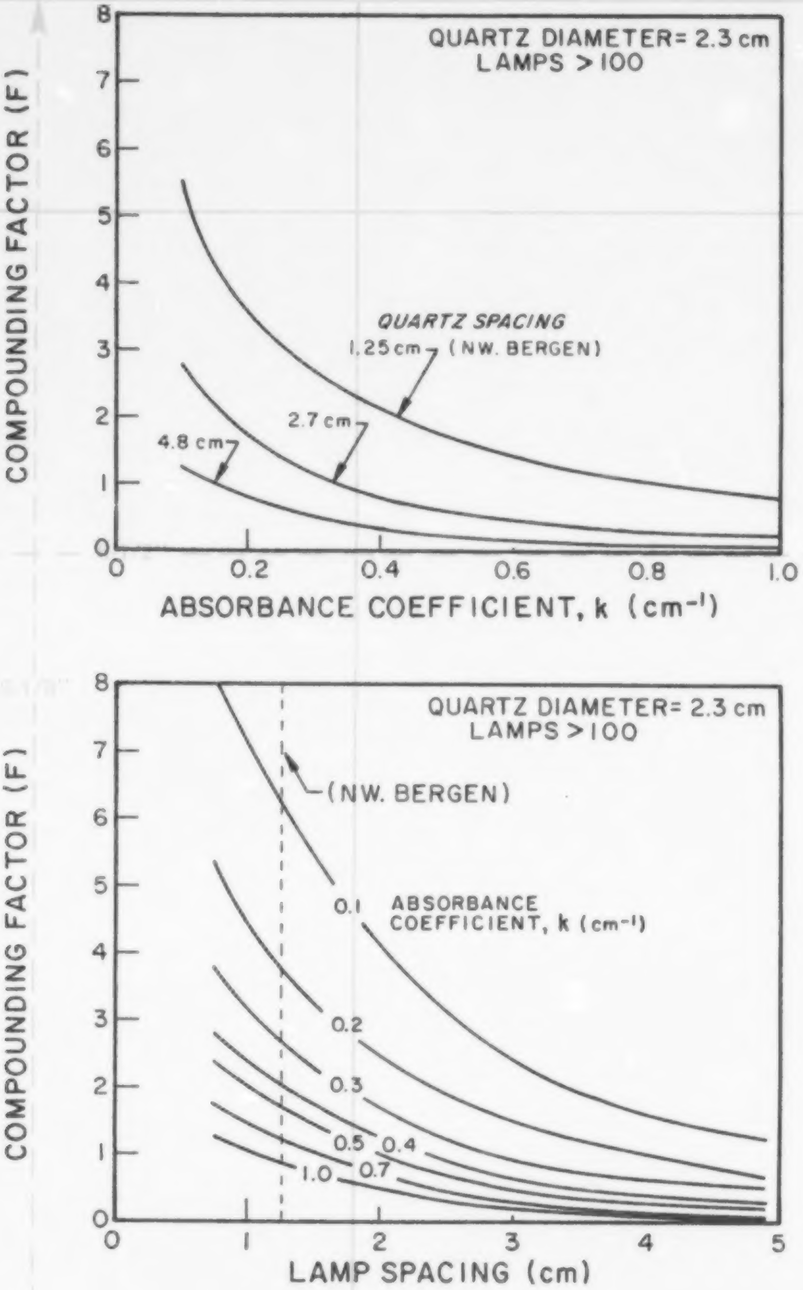

Figure 14. Compounding factors at various lamp spacings and absorbance coefficients.

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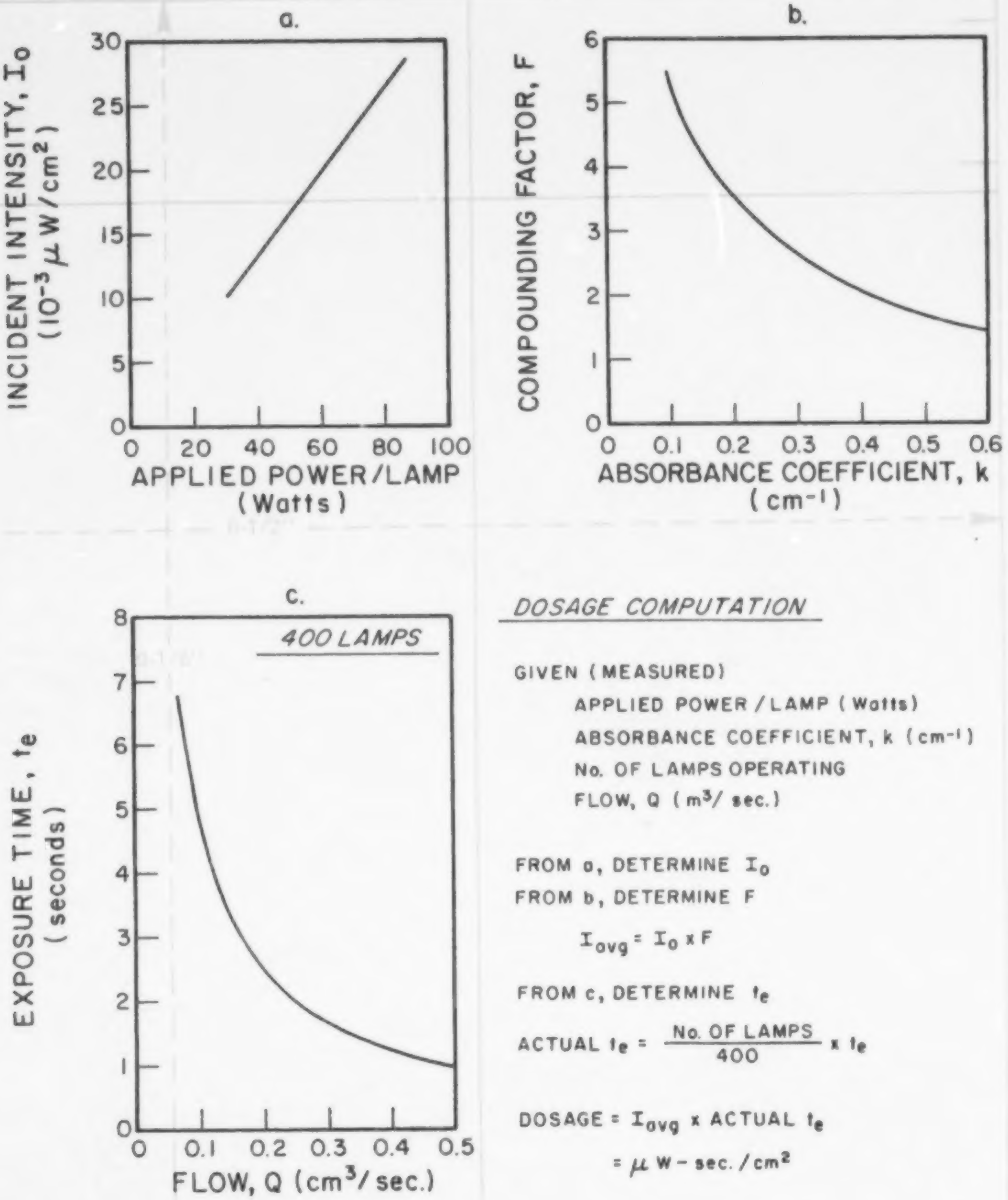

DOSAGE COMPUTATION

GIVEN (MEASURED)
APPLIED POWER / LAMP (Watts)
ABSORBANCE COEFFICIENT, k (cm^{-1})
No. OF LAMPS OPERATING
FLOW, Q (m^3/ sec.)

FROM a, DETERMINE I_o
FROM b, DETERMINE F

$I_{avg} = I_o \times F$

FROM c, DETERMINE t_e

$$\text{ACTUAL } t_e = \frac{\text{No. OF LAMPS}}{400} \times t_e$$

$$\text{DOSAGE} = I_{avg} \times \text{ACTUAL } t_e = \mu\text{W-sec./cm}^2$$

Figure 15. Calculation of applied dosage.

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Incident Intensity, I_o

The incident intensity at the quartz surface was computed by the expression,

$$I_o = \frac{(AP \times 10^6)(0.35)(0.9)}{A_Q} \qquad (6\text{-}9)$$

where:

I_o = incident intensity at the quartz surface (μ W/cm^2)

AP = applied power per lamp (Watts)

A_Q = surface area of the quartz enclosure

The area, A_Q, was 1000 cm^2 in the case of the NW Bergen system. AP was a measured value, and the factor 10^6 converts watts to microwatts. The factor 0.35 accounts for the rated U.V. output at 253.7 nm, which is 35% of the nominal power rating of the lamp. The factor 0.9 accounts for an assumed 10% absorbance by the quartz enclosure. Direct measure of the power/lamp was found to account sufficiently for lamp aging.

As was discussed in Section 4, a feature of the system was an ability to vary the applied voltage between 40% and 100% of total voltage rating. Below 40% the lamps would shut-off. The above expression (6-9) assumes that the intensity is linear with the power application and that a reduction in power will yield an equivalent reduction in U.V. intensity. This may, in fact, be a conservative estimate; data from N.W. Bergen indicated that the intensity falloff is not as rapid as the power falloff. There was not a significant difference however, and for the sake of convenience the intensity and power reductions were assumed to be equivalent. The solution of expression (6-9) for the NW Bergen application is presented on Figure 15a. Given the observed power application per lamp, the value of I_o was then determined.

Compounding Factor, F

The compounding factor can be determined for a particular system configuration, given the absorbance coefficient, k, of the wastewater. The solution shown on Figure 15b was used for the NW Bergen system (this solution had also been presented on Figure 14).

Average Intensity, I_{avg}

The average intensity was computed as

$$I_{avg} = I_o \times F \tag{6-10}$$

where:

I_{avg} = Average Intensity ($\mu W/cm^2$)
I_o = Incident Intensity ($\mu W/cm^2$)
F = Compounding factor

Exposure Time, t_e

The exposure time was computed directly for the NW Bergen system as a function of the void volume and flow. Figure 15c is a solution for exposure time as a function of flow when all 400 lamps are operating. In a situation where only a fraction of the lamps were operational, the fraction was applied to the t_e determined from Figure 15c.

Applied U.V. Dose, D

The dose was finally computed as

$$D = I_{avg} \times t_e \tag{6-11}$$

where:

D = Ultraviolet dose ($\mu W\text{-}sec/cm^2$)
I_{avg} = Average intensity ($\mu W/cm^2$)
t_e = Exposure time (seconds)

As an example, consider the following sampling data on the system utilized in the NW Bergen study,

Power/Lamp (AP) = 50 watts
Absorbance Coefficient (k) = 0.4 cm^{-1}
No. of Lamps in Operation = 300
Flow (Q) = 0.25 m^3/sec

From Figure 15a,

$$I_o = 16{,}500 \ \mu W/cm^2$$

From Figure 15b,

$$F = 2.1$$

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This yields an $I_{avg} = 34{,}650\ \mu W/cm^2$.

From Figure 15c, the exposure time at $Q = 0.25\ m^3/sec$ would be 2 seconds if all lamps were operating. For 300 operable lamps,

$$t_e = 300/400\ (2.0) = 1.5 \text{ seconds.}$$

The dose under these specified operating and water quality conditions is then estimated to be

$$D = I_{avg} \times t_e$$

$$D = 34{,}500\ \mu W/cm^2 \times 1.5 \text{ seconds}$$
$$D = 51{,}750\ \mu W\text{-}sec/cm^2$$

The same calculation procedure was used to estimate the dose for each sampling of the NW Bergen study, and the values were used in all subsequent data analyses.

Table 4 presents a comparison of the dose-response relationship developed as part of this study with the results of a limited number of ultraviolet disinfection studies reported in the literature. These studies (23,24,35) investigated the application of submerged ultraviolet systems to secondary effluents. There are three investigations listed; study C represented several "runs," each of which is listed as U1 through U8. The second column presents the U.V. dose reported by each investigator to achieve the effluent fecal coliform levels shown in Column 3. There is not a clear correlation of dose with response. More importantly, there was no agreement among the three studies shown (as well as others reported in the literature) as to their method of dose calculation and reporting.

The values presented in Column 4 are doses which have been estimated by the procedure described in this report, based on the system specifications listed for each of the studies. The last column gives the approximate mean fecal coliform density which would be predicted at these dose levels, using the dose-response curve developed from the NW Bergen investigation. An exact correlation with the effluent fecal coliform levels reported by the three studies is not expected. However, it is evident that revised doses shown in Column 4 are effective in predicting the level of response. There is a strong correlation between the predicted response and the reported, or measured responses.

TABLE 4

LITERATURE COMPARISON OF DOSE CALCULATION

Study	Reported[2] Ultraviolet Dose (μW-sec/cm^2)	Reported[4] Response, Mean Effluent FC (MPN/100 ml)	Revised[5] Ultraviolet Dose (μW-sec/cm^2)	Predicted[6] Response, Mean Effluent FC (MPN/100 ml)
A	60,000	<2	110,000	30
B	(3)	7-70	60,000-100,000	50-200
C-U1	37,200	<2.3	130,000	20
U2	30,500	<3.1	125,000	20
U3	57,800	<2.0	110,000	30
U5	12,300	>280	66,000	200
U6	10,800	>2,000	18,000	3,000
U7	17,000	<100	45,000	300
U8	11,500	320	37,000	400

(1) A; Reference 35
B; Reference 23
C; Reference 24

(2) Dose reported by investigators.

(3) Dose term was not reported.

(4) Reported effluent fecal coliform levels (after irradiation).

(5) Based on the reported system design, the dose was recomputed by the procedure discussed within this report.

(6) This prediction is based on the dose-response curve developed for the NW Bergen.

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Albeit preliminary, the above analysis suggests that the dose calculation procedure is a uniform methodology which provides a reasonably accurate estimate of the dose application. This in turn provides a rational parameter for U.V. system design, as will be discussed in a later section.

SECTION 7

RESULTS AND DISCUSSION

The experimental field study for the ultraviolet disinfection project extended over the period of March 1978 thru April 1979, a total of thirteen months. In all, the investigations resulted in a considerable store of data, which for convenience, have been compiled and are documented in a separate supplemental report entitled "Ultraviolet Disinfection Project Field Data Report."

The following discussions are a presentation of the results of the field investigation, the analyses of which were directed to the major topics of interest:

- characterization of plant effluent quality as it relates to the application of ultraviolet disinfection,
- definition of dose-response relationships,
- demonstration of U.V. system capability to consistently meet prescribed effluent criteria,
- analysis of factors which influence the application of an ultraviolet dose,
- characterization of operation and maintenance requirements for the system.

The results of the photoreactivation analyses are presented in a subsequent section, as are the design and costs analyses.

WATER QUALITY CONSIDERATIONS

Plant Performance Characterization

Before presentation of the results of the field study, it is useful to first consider the performance of the Northwest Bergen Water Pollution Control Plant in terms of final effluent quality. The average data are summarized on Table 5. The table also presents 95% confidence limits as defined by the mean ± 1.95σ. Figures 16, 17, and 18 are chronologic records of a

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TABLE 5

SUMMARY OF NW BERGEN WPCP EFFLUENT ANALYSIS
(APRIL 1979 THRU APRIL 1979)

Parameter	Mean	95% Confidence Limits (± 1.95σ)	No. Analyses
Total Coliform (MPN/100 ml)	1.9x10^{5}+	1.4x10^{4}-2.4x10^{6}	361
Fecal Coliform (MPN/100 ml)	4.8x10^{4}+	2.3x10^{3}-9.8x10^{5}	358
COD(F)* (mg/l)	28	26-30	327
Suspended Solids (mg/l)	6.5	0-14	355
Turbidity (NTU)	3.7	0-11	353
pH	7	6.7-7.5	356
TKN(F) (mg/l)	14	0.2-29	180
NH_3-N (mg/l)	12	0-24	182
NO_2-N (mg/l)	1.0	0-2.4	161
NO_3-N (mg/l)	7.5	6.5-8.5	161
Temperature (C)	17	8-25	365
Color (PCU)	35	12-58	168
Absorbance Coefficient (cm^{-1})(1)	0.39	0.22-0.55	350
Transmittance (%)	68	57-79	350

(1) 1 cm cell at 253.7 m

*Note: (F) = filtered

+Geometric mean

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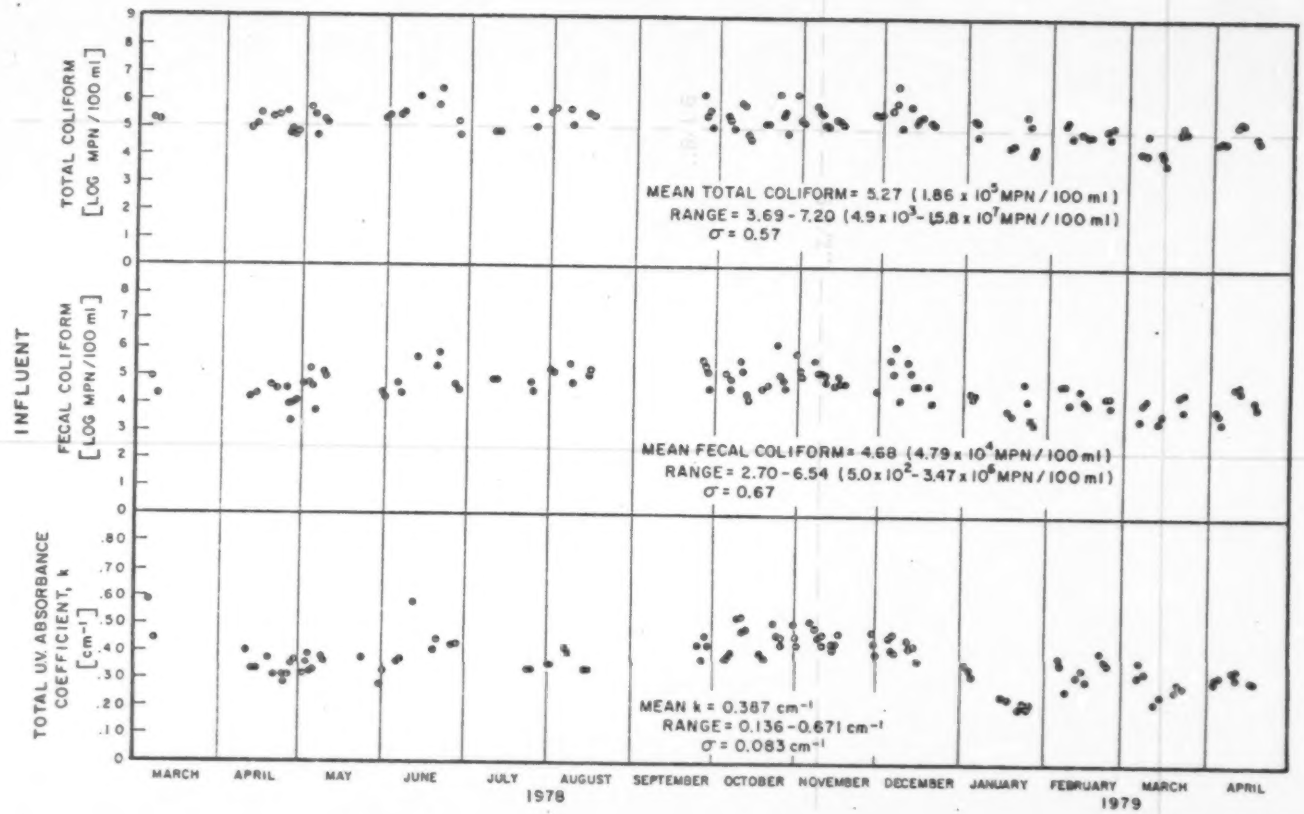

Figure 16. Chronologic record of influent coliform and U.V. absorbance coefficient.

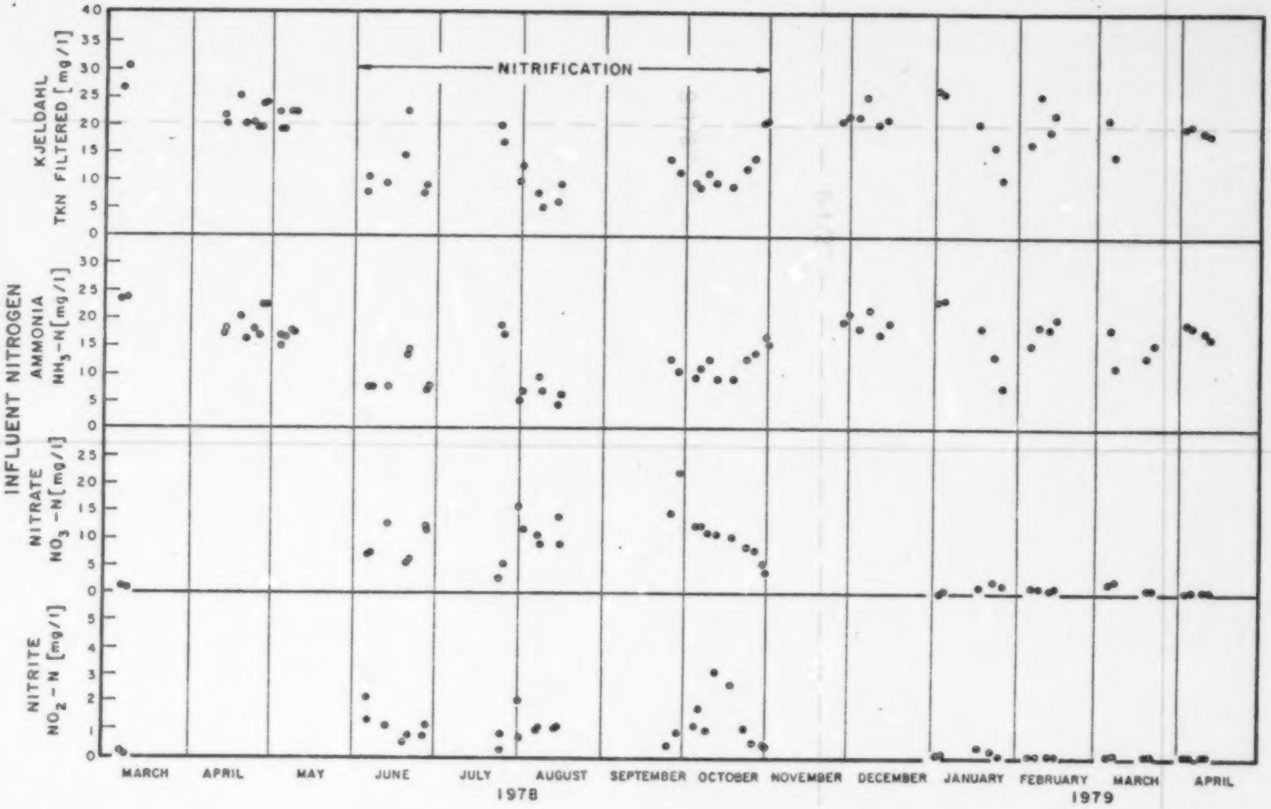

Figure 17. Chronologic record of influent Kjeldahl, Ammonia, Nitrate, and Nitrite Nitrogen.

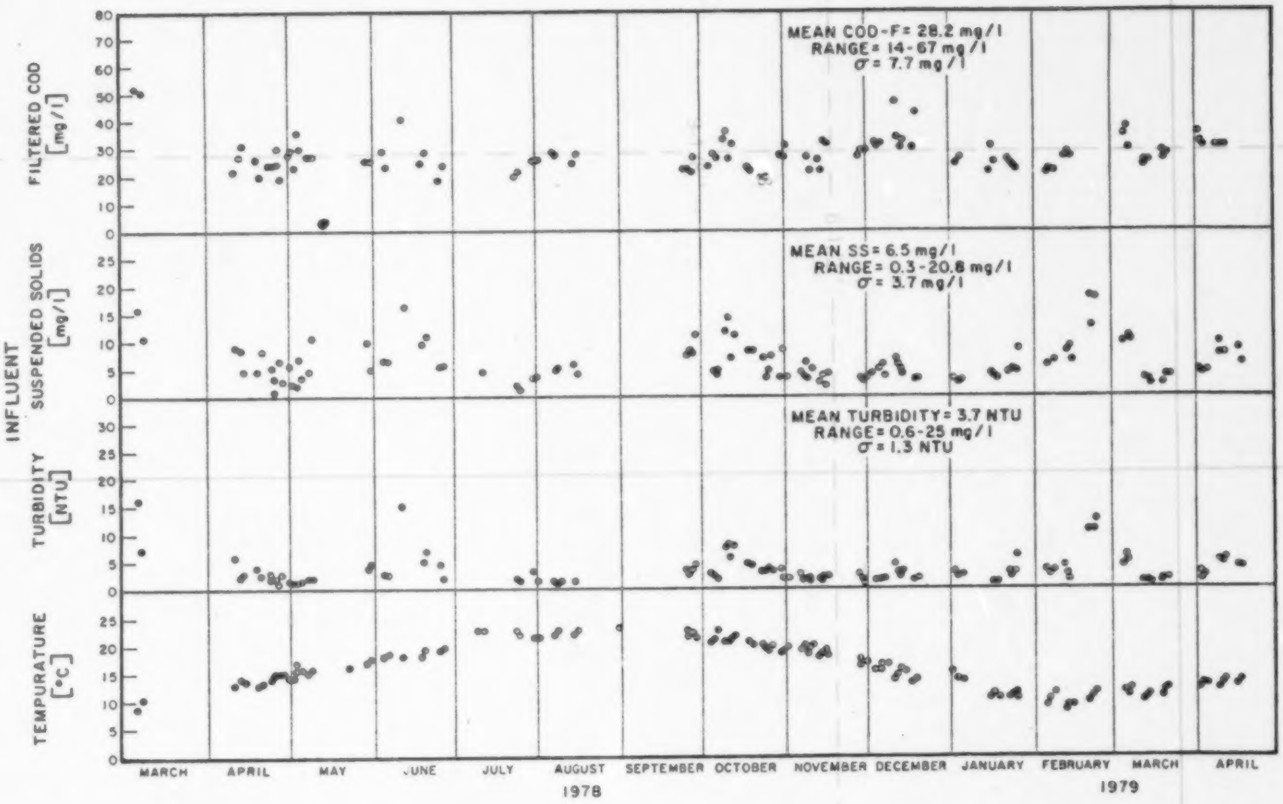

Figure 18. Chronologic record of influent filtered COD, Suspended Solids, Turbidity, and Temperature.

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number of the more significant U.V. unit influent wastewater quality parameters. All analyses were performed on grab samples, typically drawn between the hours of 10:00 A.M. and 3:00 P.M. The observed data presented in the Figures represent averages in cases where several grabs were taken in a single day.

Figure 16 presents the total and fecal coliform density data. The mean total coliform was 1.9 X 10^5 MPN/100 ml and the mean fecal coliform was 4.8 X 10^4 MPN/100 ml for the total term of the project. The U.V. absorbance coefficient (unfiltered samples) averaged 0.39 cm^{-1}, with a coefficient of variation of 21%. The equivalent U.V. transmittance averaged 68% and ranged from 57 to 79%.

The nitrogen series analytical results are presented on Figure 17. These parameters were monitored routinely to characterize the NW Bergen plant's mode of operation. During the warmer months the plant was required to achieve a degree of ammonia removal by nitrification. This is evidenced by the high nitrite and nitrate concentrations during the months of June thru October. The concentrations of these same parameters approach zero during the remainder of the year, with consequent increases in the total kjeldahl and ammonia concentrations. No significant changes in the average levels of other measured water quality parameters, including coliform densities, were evidenced by the alternate plant operational modes.

Figure 18 displays influent COD, SS, turbidity, and temperature data. The filtered COD averaged 28 mg/l, and exhibited a coefficient of variation of 27%. Suspended solids and turbidity were typically low, averaging 6.5 mg/l and 3.7 NTU, respectively. The coefficients of variation were higher for these two parameters (57% for SS and 35% for turbidity), due in large part to the imprecision of the analytical procedures at such low levels. The temperature data show the seasonal variation typical of the northeast region.

Generally, the data represent an effluent of very consistent quality, particularly in view of the fact that these were grab samples. There was little evidence of significant deviation throughout the term of the project. This lack of variability, in fact, limited the extent of data analyses relating water quality variations with ultraviolet disinfection efficiency.

Correlation of Wastewater Quality Parameters

The efficiency of ultraviolet irradiation in the disinfection of an aqueous medium is strongly related to the quality of the medium. The presence of contaminants in the water which will absorb the radiant energy will obviously detract from the ability to destroy microorganisms. This fact is implicit in the expression for ultraviolet dose, in which an absorbance coefficient accounts for attenuation of the light intensity by the absorption of energy.

Several wastewater quality indexing parameters were monitored with each sample drawn during the NW Bergen field study. COD and ultraviolet absorbance (at 253.7 nm) were analyzed as a measure of organic content. Suspended solids and turbidity were measured to characterize the light scattering or shadowing properties of the wastewater medium. These data were analyzed to determine an effective parameter by which to index treatment quality and plant effluent coliform density levels. This indexing parameter would be most useful as a requisite for U.V. system design.

Linear regression analyses were conducted to evaluate the correlations of the various parameters with each other, and, in particular, with total and fecal coliform density. Table 6 summarizes these comparisons with coliform density. As would be expected, the total coliform and fecal coliform measurements are strongly correlated. Of the four water quality indices tested, only the U.V. absorbance coefficient was found to be correlated with the coliform density levels. Correlation coefficients of 0.53 and 0.606 were determined for total and fecal coliform, respectively, indicating a possible linear relationship. Significant correlations were not found between coliform density and turbidity, suspended solids, or COD.

The U.V. absorbance coefficient was found to also correlate significantly with the COD, turbidity, and suspended solids concentrations. The results of the linear regression analyses are presented on Table 7. Stepwise multiple linear regression analyses were not found to significantly improve the correlations. In light of these results and the strong correlation exhibited with coliform density, it is judged very appropriate to use the U.V. absorbance coefficient as the major water quality parameter in U.V. system design and dosage application.

Impact of Ultraviolet Irradiation on Wastewater Quality

During the initial period of the project, both influent and effluent samples were analyzed for the full schedule of wastewater parameters in order to assess the impact, if any, of exposure to ultraviolet irradiation on these parameters (at levels required for disinfection). Note that this analysis was also conducted for non-volatile organics and has been reported elsewhere (28).

Student's "t" test was used to check for any significant difference between the influent and effluent data. The null hypothesis tested was that the mean difference between the influent and effluent data was equal to zero. The results are

TABLE 6

CORRELATION OF WATER QUALITY PARAMETERS WITH EFFLUENT COLIFORM DENSITIES PRIOR TO UV DISINFECTION

	Log Total Coliform			Log Fecal Coliform		
Parameter	Regression Equation	No. of Samples n	Correlation Coefficient r	Regression Equation	No. of Samples n	Correlation Coefficient r
Log Total Coliform	-	-	-	Log TC = 0.72 log FC +1.92	355	0.843
Absorbance Coefficient (unfiltered)	Log TC = 3.68k + 3.86	350	0.534	Log FC = 4.95k + 2.78	340	0.606
Turbidity	N.S.	349	0.177	N.S.	345	0.133
Suspended Solids	N.S.	350	0.200	N.S.	346	0.182
COD-Filtered	N.S.	322	0.064	N.S.	318	0.042

N.S. - Not significant (95%)

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TABLE 7

CORRELATION OF U.V. ABSORBANCE COEFFICIENT WITH COD, TURBIDITY AND SUSPENDED SOLIDS

Parameter	Correlation with Total U.V. Absorbance Coefficient, k Regression Equation	No. of Samples n	Correlation Coefficient, r
Suspended Solids	k = 0.010 SS + 0.322	353	0.447
Turbidity	k = 0.011 Turb + 0.347	352	0.494
COD - Total	k = 0.004 COD-T + 0.270	173	0.549
COD - Filtered	k = 0.004 COD-F + 0.270	326	0.377

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summarized on Table 8 for each parameter. As shown, the calculated t value in all cases is less than 2.005, which is the significant value at the 95% confidence level. Thus the analysis fails to reject the hypothesis, indicating insignificant impact of the U.V. radiation on the various water quality parameters.

DOSE-RESPONSE

The dose-response relationship is basic to ultraviolet disinfection analysis and system design. Given an accurate measure of dose and a measured response in terms of bacterial kill, reasonable judgments of design requirements can be made to achieve a desired bacterial density.

First Order Dose-Response Relationships

Typically, the dose-response relationship has been described as a first order linear relationship,

$$\frac{dN}{dt} = -yNI \qquad (7\text{-}1)$$

where:

N = bacterial density at time, t
t = time of exposure
I = the average ultraviolet intensity in the exposure chamber
y = rate constant

Integration of the above expression yields the relationship

$$\frac{N}{N_o} = e^{-yIt} \qquad (7\text{-}2)$$

where:

N_o = the initial bacterial density

This expression indicates a dependency of the effluent density on both the dose (It) and the initial coliform density. The term N/N_o is often referred to as the surviving fraction. Most curves based on this expression, however, show a marked tailing as the log surviving fraction is reduced to low levels, which is the range of coliform densities where disinfection processes normally operate. Figure 19 presents the first order expression developed for this study, where the tailing effect is apparent at the lower log surviving fraction levels.

TABLE 8

IMPACT OF ULTRAVIOLET LIGHT ON WATER QUALITY

(TEST OF DIFFERENCES)(1)

Parameter	Mean Difference (Inf-Eff) (56 Samples)	Calculated(2) t-value
COD(T)	-0.48	0.87
COD(F)	-1.0	1.71
Color	-0.8	0.9
U.V. Absorbance (T)	-0.0028	1.39
U.V. Absorbance (F)	0.0007	0.53
TSS	0.19	1.37
Turbidity	0.18	0.84
TKN(F)	-2.45	1.37
NO_2-N	0.011	0.73
NO_3-N	0.041	0.55
NH_3-N	-0.085	0.79

(1) Student t analysis. Null Hypothesis, H_o, is that the difference between the influent and effluent of the U.V. unit is equal to zero.

(2) Significant at $t > 2.005$

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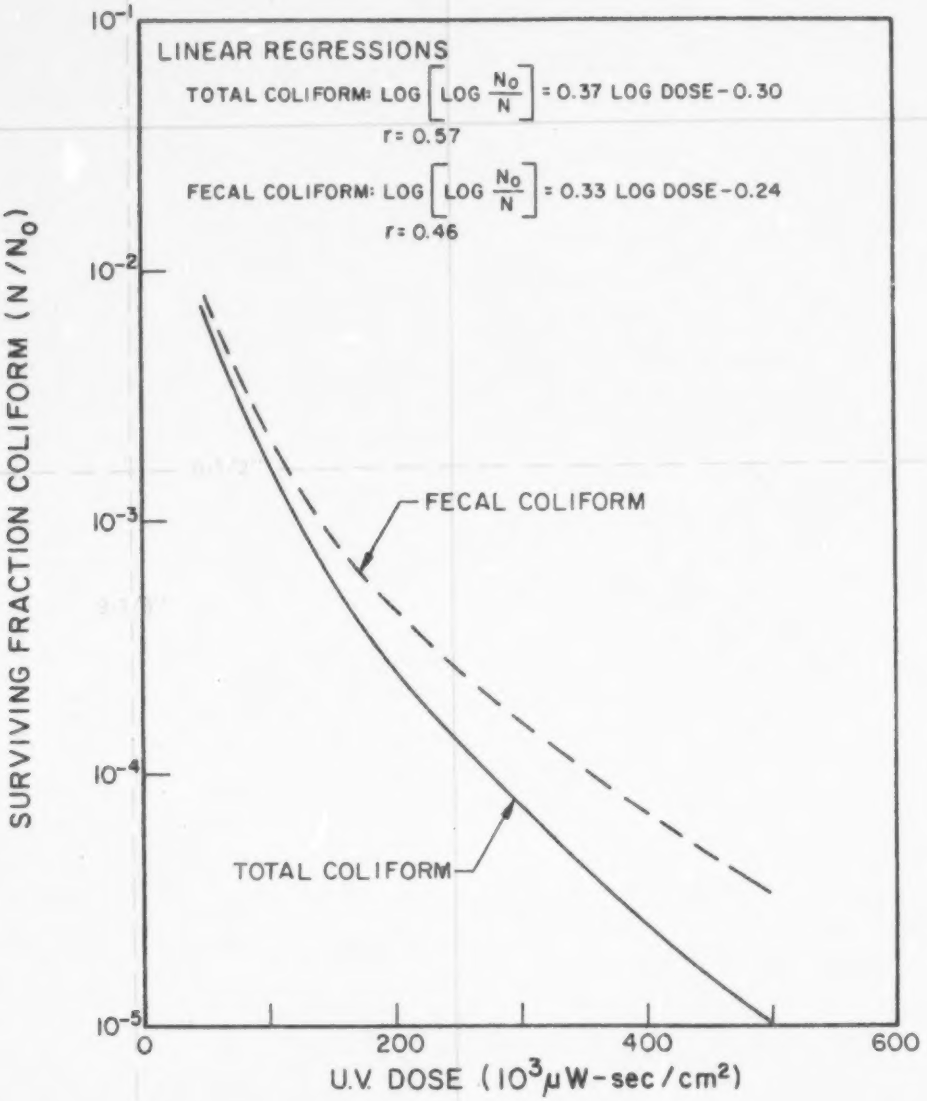

Figure 19. First order dose-response relationships.

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It was found that the log transformation of the first order expression was linear. The linear regression (least squares analysis) equations were as follows:

Total Coliform,

$$\text{Log}\ (\text{Log}\ \frac{N_o}{N}) = 0.37\ \text{Log Dose} - 0.30 \qquad (7\text{-}3)$$

Fecal Coliform,

$$\text{Log}\ (\text{Log}\ \frac{N_o}{N}) = 0.33\ \text{Log Dose} - 0.24 \qquad (7\text{-}4)$$

The correlation coefficients for these regressions were 0.57 for total coliform and 0.46 for fecal coliform.

Second Order Dose-Response Relationships

The tailing effect, experienced when survival ratios are low, may be accounted for by defining a second order relationship with respect to the coliform density:

$$\frac{dN}{dt} = yN^2I \qquad (7\text{-}5)$$

Integration of this expression yields

$$\frac{1}{N} - \frac{1}{N_o} = yIt \qquad (7\text{-}6)$$

Linear regressions, based on the log transformation of this relationship, were found to provide significantly better correlations than those based on the first order log transformed relationship (Equations 7-3 and 7-4). The dependency on the initial density remains, but obviously to a far lesser degree. This fact can be exploited in order to simplify the second order expression. If one can assume the initial coliform density, N_o, to be much greater than the final density, N, the term $1/N_o$ becomes insignificant relative to the effluent density:

$$\frac{1}{N} >> \frac{1}{N_o}$$

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and expression (7-6) can be reduced to

$$\frac{1}{N} = yIt \qquad (7\text{-}7)$$

It is suggested that this assumption is appropriate when the expected coliform reduction is greater than an order of magnitude (i.e. one log reduction). This is generally the case when considering the disinfection of secondary effluents.

Linear regressions (by the least squares approximation) of the log transformed effluent density and dose were found to provide excellent linear correlations and confirmed the assumption of approximating second order kinetics. Figure 20 displays the regression of the log effluent total coliform and the log dose. The observed data represent approximately 350 samplings. The regression equation is,

$$\text{Eff TC} = (1.26 \times 10^{14})\ D^{-2.35} \qquad (7\text{-}8)$$

where:

Eff TC = effluent total coliform (MPN/100 ml)

D = ultraviolet dose (W-sec/cm^2)

The correlation coefficient for this regression was 0.7, indicating that approximately 50% of the variance in the effluent total coliform data was explained by the relationship. This is a substantial improvement over the correlation derived from the first order log transformed relationship, where 32% of the variance was explained.

Figure 21 displays the log effluent fecal coliform density - log dose regression. The regression expression in this case was,

$$\text{Eff FC} = (1.25 \times 10^{13})\ D^{-2.27} \qquad (7\text{-}9)$$

where,

Eff FC = effluent fecal coliform density (MPN/100 ml)

D = ultraviolet dose (W-sec/cm^2)

A correlation coefficient of 0.66 was determined. This indicates that expression (7-9) accounts for 44% of the

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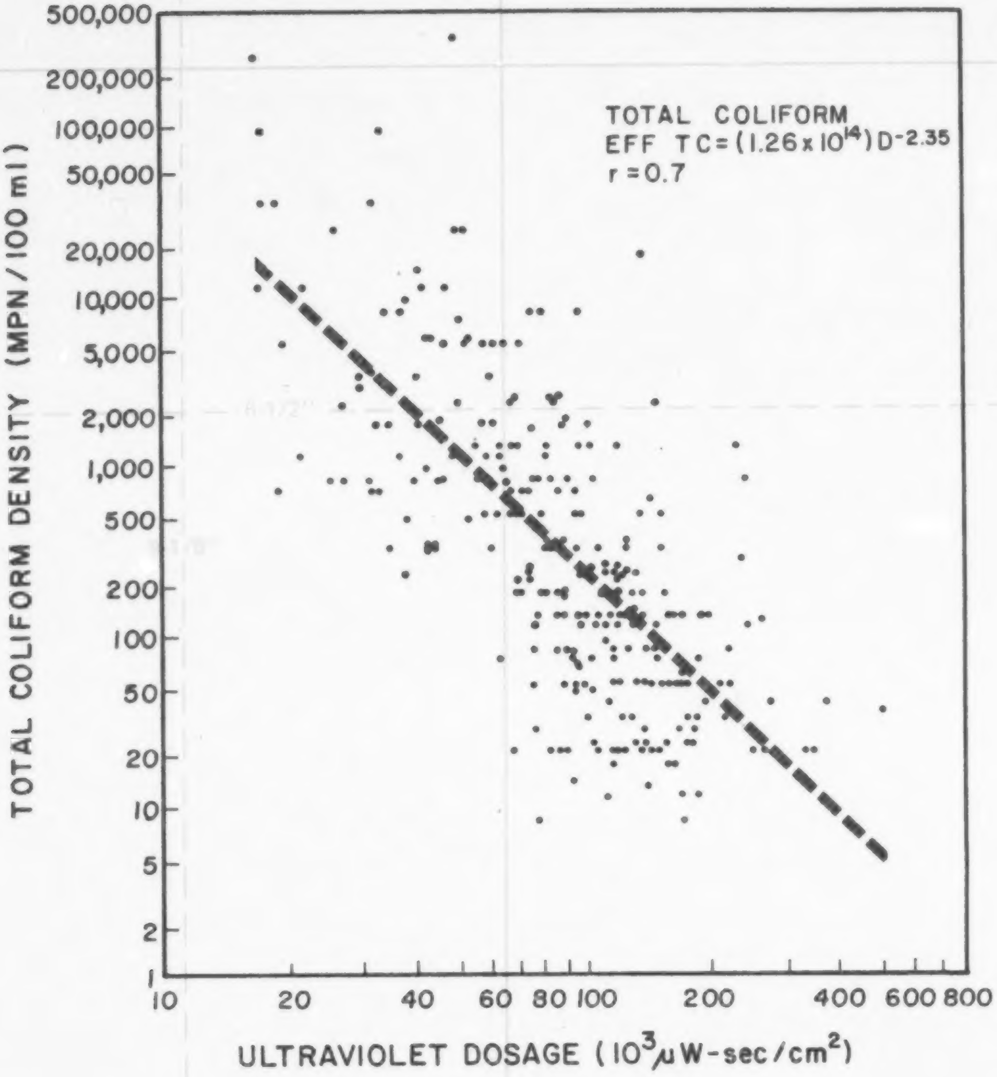

Figure 20. Second order dose-response relationship for total coliform.

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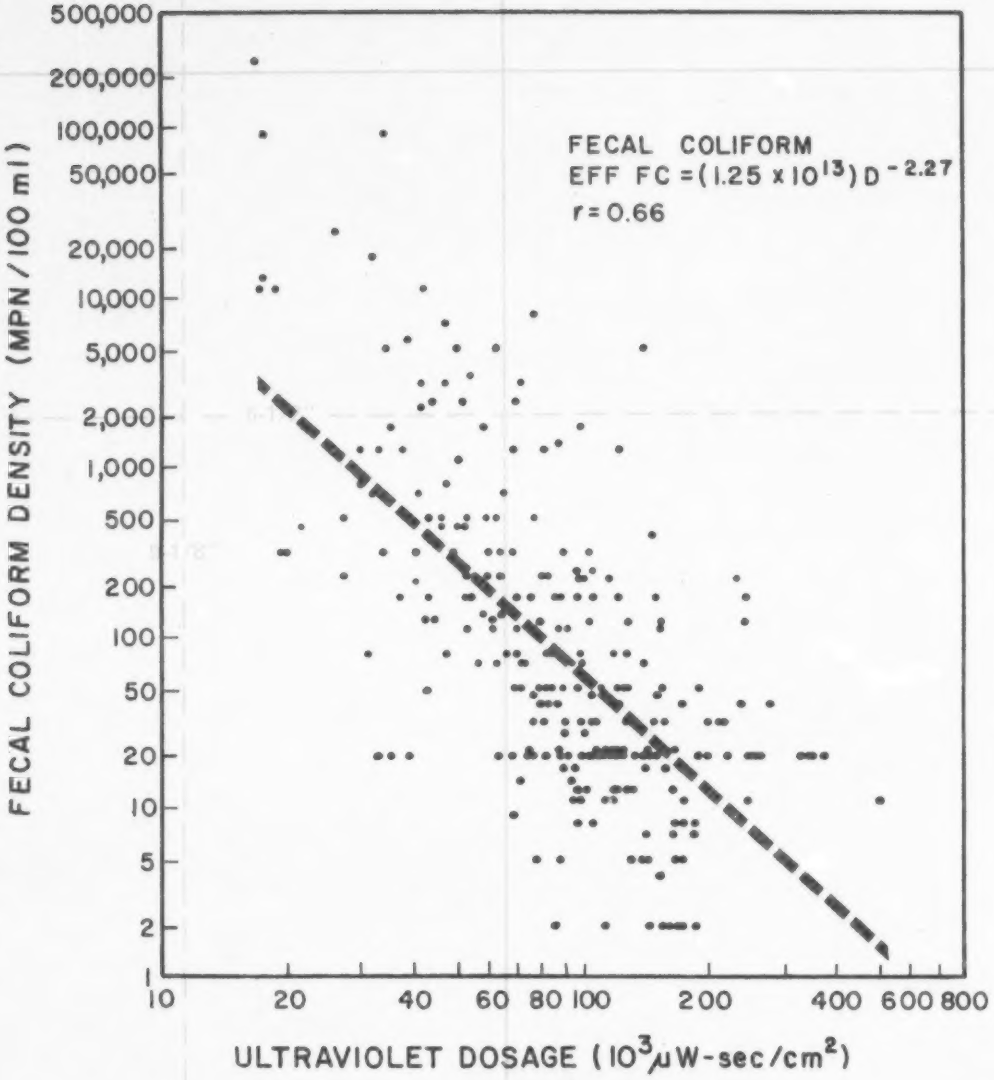

Figure 21. Second order dose-response relationship for fecal coliform.

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variance in the effluent fecal coliform data. This is an improvement over the first order expression which accounted for 21% of the variance.

The linear regression analysis for fecal streptococcus data is presented in Figure 22. The data base in this case was far smaller than was available for either total or fecal coliform, with approximately 35 samplings. The regression equation is,

$$\text{Eff FS} = (5.66 \times 10^{18})\ D^{-3.31}$$

where,

Eff FS = effluent fecal streptococcus density (MPN/100 ml)

D = ultraviolet dose (μW-sec/cm^2).

The correlation coefficient in this case was 0.61, which indicates that the regression equation accounts for 37% of the variance in the fecal strep data.

Impact of Temperature

The impact of temperature on germicidal efficiency can be by two mechanisms. The first is when the water medium acts as a heat sink to the lamps, drawing the lamp temperature down to levels where the U.V. output from the lamp is significantly reduced. The optimum lamp operating temperature is approximately 43°C for maximum intensity output. Analysis of lamp temperature data at the maximum voltage setting indicated little evidence of variability as a function of water temperature. At an average water temperature of 21.3°C, the average lamp temperature was at the optimal level of 43.0°C, with an applied voltage of 450 V. At the same applied voltage, the average lamp temperature was reduced to 40.0°C at an average water temperature of 10.5°C. Thus for a water temperature differential of 10.8°C, there was a lamp temperature change of 3°C, which represented a 7.5% decrease from the optimum lamp temperature. This was not considered significant.

The second mechanism by which temperature may influence the efficiency of the U.V. system is by having an impact on the rate of disinfection. Two approaches were taken to evaluate this effect. In the first, the second order relationship for fecal coliform survival was evaluated by a least squares analysis, using data collected at temperatures greater than 21.5°C and less than 12°C. The regression equations are displayed on Figure 23. The analysis was conducted to determine whether there was a significant difference in the coliform reduction rate over the temperature range generally experienced in

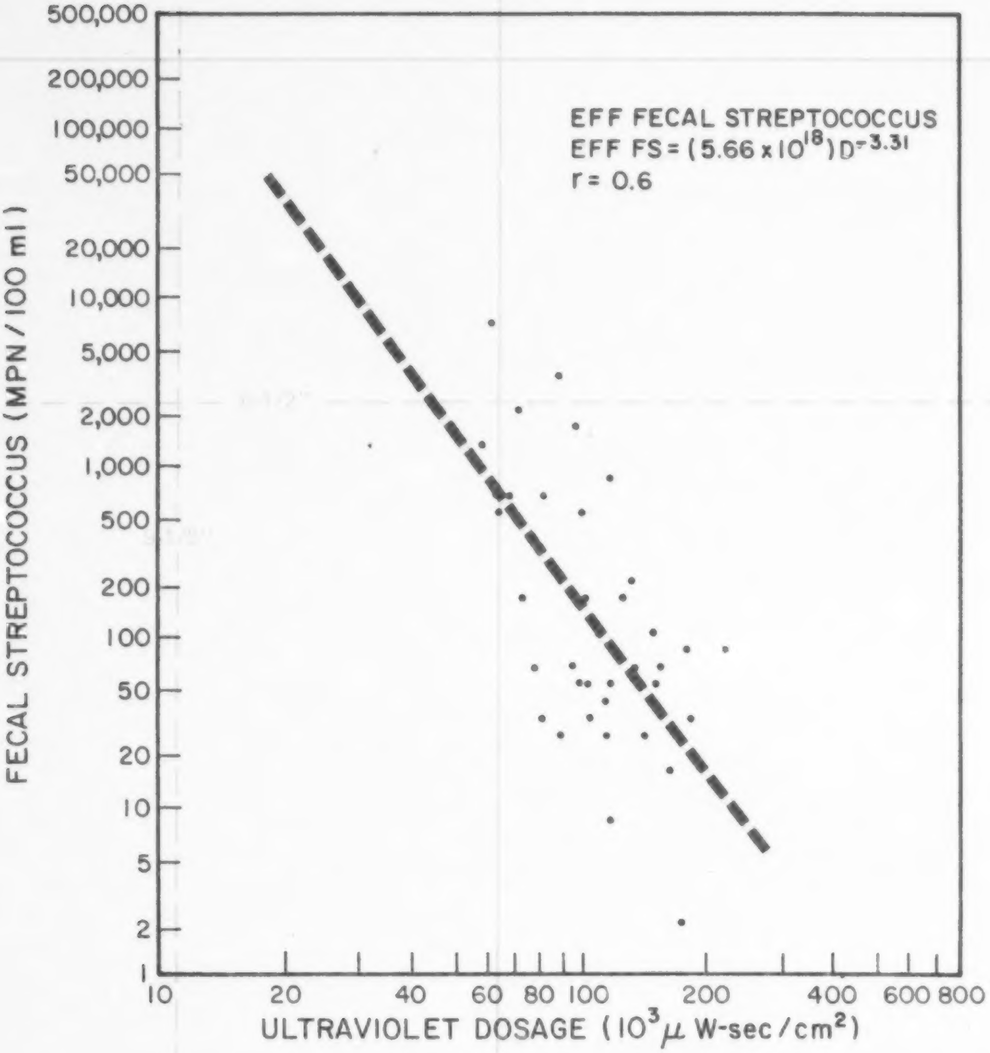

Figure 22. Second order dose-response relationship for fecal streptococcus.

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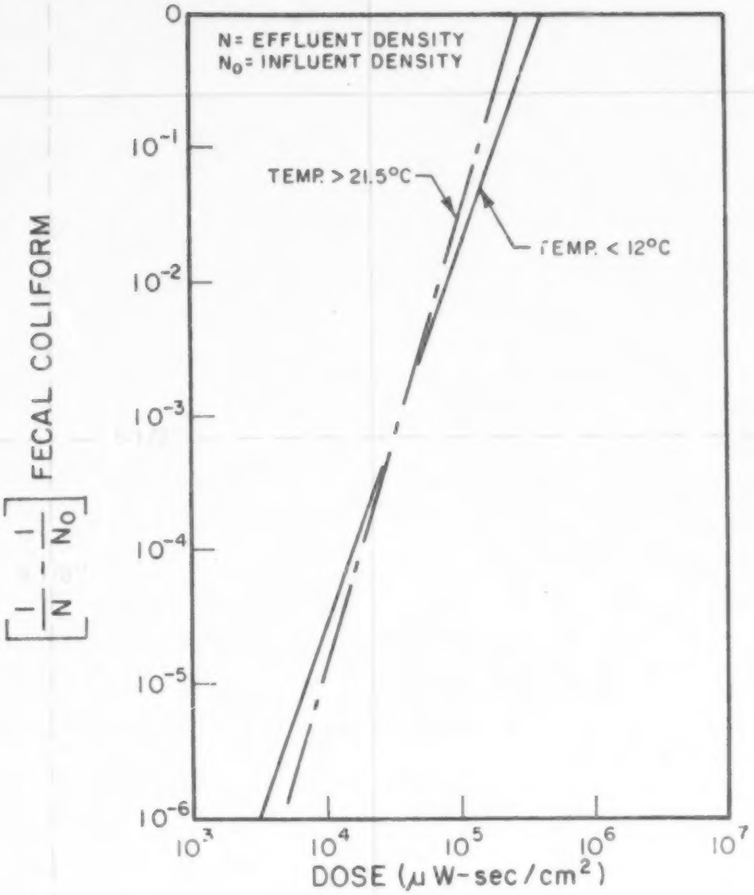

Figure 23. Temperature effects on disinfection rate.

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wastewaters. As evidenced by Figure 23, there is little difference in the rates determined for each temperature regime. Both functions, in fact, fall within the range obtained by varying the rate by one standard deviation for either function. A temperature dependence was considered insignificant, based on this analysis.

A multiple regression analysis was also performed to evaluate temperature effects, with effluent coliform density the dependent variable and temperature and dose the independent variables. The entire data record was utilized for this analysis and the results indicated that temperature was not significant at the 5% level.

Analysis of Secondary Impacts on Dose-Response Relationships

The ultraviolet dose is calculated on the basis of water quality and unit operational mode. Dose can be controlled by varying the number of lamps engaged, varying the applied voltage, or by changing the flow through the unit. Dose would also change with the water quality, as measured by the absorbance coefficient.

The ratio of the observed coliform density and the predicted coliform density was regressed against the independent variables which influence the applied dose. In this case both coliform levels were expressed as,

$$\log\left(\frac{1}{N} - \frac{1}{N_o}\right)$$

These relationships were developed to determine whether the major operational or water quality variables produced a residual effect on coliform density which was unexplained by the dosage expression. The slope of the ratio of the observed/estimated coliform function vs. the variable of concern (other factors remaining constant) would approximate zero if there was no residual trend.

Table 9 summarizes the correlation coefficients derived for the regression of the observed/estimated ratio for total and fecal coliform versus six variables relating to water quality and unit operations. As shown in Table 9, the U.V. absorbance coefficient, the initial coliform density, the temperature, the number of lamps engaged, and the applied voltage do not contribute to any unexplained residual scatter in the dose-response relationship. An example of this residual analysis is graphically displayed on Figure 24. The Figure shows the observed/estimated ratio for both total and fecal coliform against the applied voltage. As can be seen there is no

TABLE 9

CORRELATION OF OBSERVED/ESTIMATED COLIFORM DENSITY RATIO WITH OPERATIONAL AND WATER QUALITY PARAMETERS

	Correlation Coefficient, r	
Parameter	Fecal Coliform(1)	Total Coliform(1)
U.V. Absorbance Coefficient	0.078 (NS)(2)	0.122 (NS)
Initial Coliform Density	0.134 (NS)	0.234 (NS)
Temperature	0.002 (NS)	0.053 (NS)
No. of Lamps Engaged	0.083 (NS)	0.189 (NS)
Applied Voltage	0.007 (NS)	0.133 (NS)
Flow	0.437 (S)	0.455 (S)

(1) Correlation with the ratio of the observed density and the estimated density. The estimated density is derived from the expressions,

$$\text{Log}\left[\frac{1}{N} - \frac{1}{N_o}\right] = 2.37 \text{ Log Dose} - 14.2 \text{ (Total Coliform)}$$

and

$$\text{Log}\left[\frac{1}{N} - \frac{1}{N_o}\right] = 2.33 \text{ Log Dose} - 13.4 \text{ (Fecal Coliform)}$$

(2) NS = Not Significant
S = Significant (5%)

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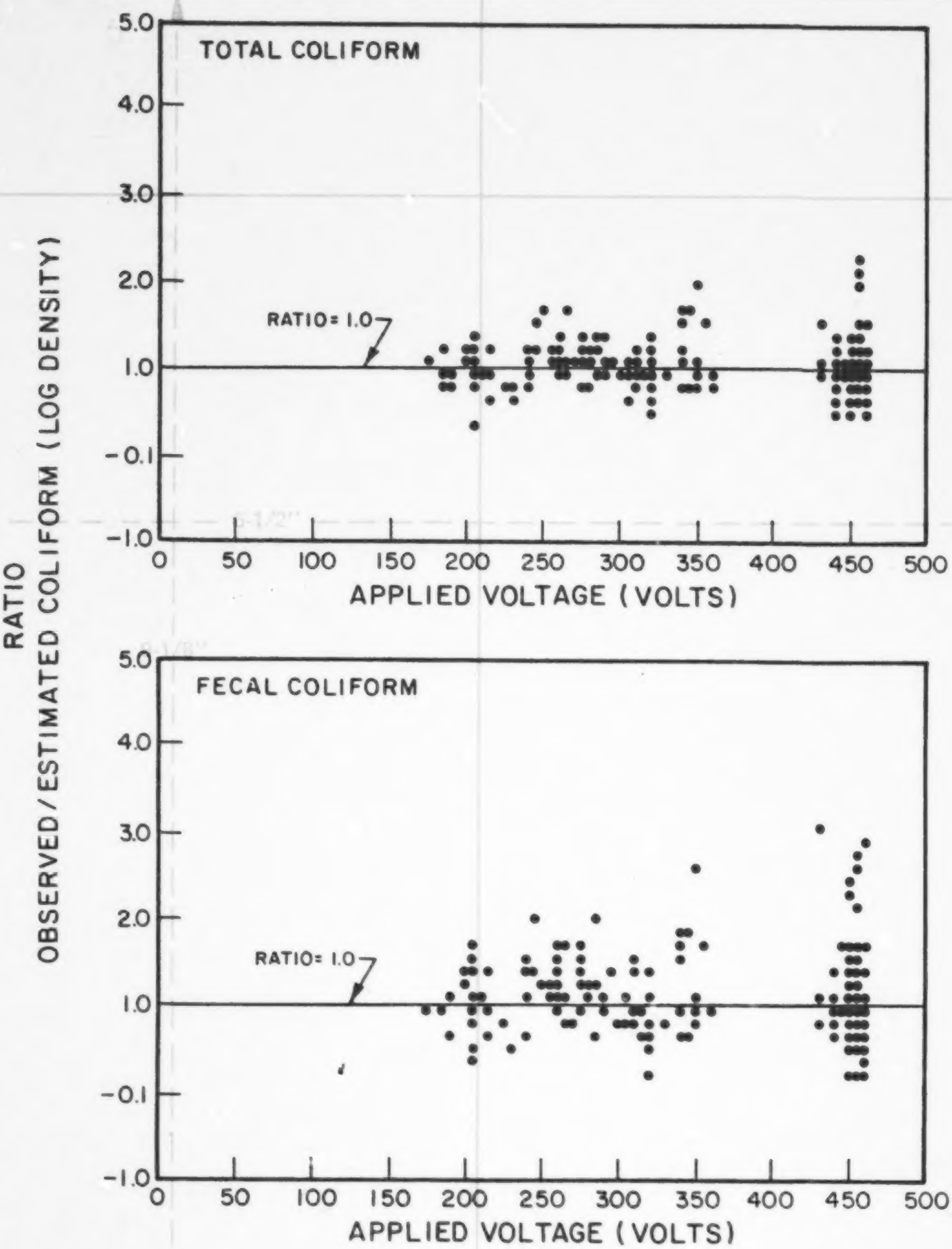

Figure 24. Example of residual analysis

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significant deviation (zero slope) from the ratio of 1.0, although there is a trend toward higher scatter as voltage increases.

The one variable which exhibited an apparently significant residual impact was the flow. As presented on Table 9 the correlation coefficients were 0.437 and 0.455 for fecal and total coliform, respectively. The graphical analysis on Figure 25 also exhibits an obvious trend, with ratios significantly higher than one at flows less than 0.16 m^3/sec. At flows greater than 0.16 m^3/sec (which was the typical operating range) there is not a significant deviation about the ratio of 1.0. There is no immediate explanation for the higher ratios in the low flow regime. It is suggested, however, that because these data represent a small portion of the total record used to develop the dose-response relationship, it is appropriate to consider the dosage expression as the independent variable which provides maximum accountability of the variance associated with effluent coliform density.

DEMONSTRATION OF LONG TERM SYSTEM OPERABILITY

Various aspects of system performance must be addressed in an evaluation of the long term capabilities of a particular unit. Those that were addressed within the time frame of this study were:

- the system's ability to consistently meet a particular set of coliform effluent criteria,
- the system's ability to operate effectively without an appreciable or costly amount of downtime,
- the operation and maintenance requirements of the unit.

Long Term Disinfection Efficiency

A four month period, covering the months of October, 1978 through January 1979, was dedicated to demonstrating the system's ability to meet a standard set of effluent criteria. These selected criteria, which are generally imposed in a majority of cases for the discharge of a secondary effluent, require that the maximum 30-day geometric mean fecal coliform density not exceed 200 MPN/100 ml and that the maximum 7-day mean not exceed 400 MPN/100 ml. Based on the preliminary results which had been derived from the summer period (June-August, 1978), a specific operational mode was set which would yield effluent densities well within these criteria. All lamps were engaged, the voltage was set to maximum and the flow was controlled about an average of 0.22 m^3/sec.

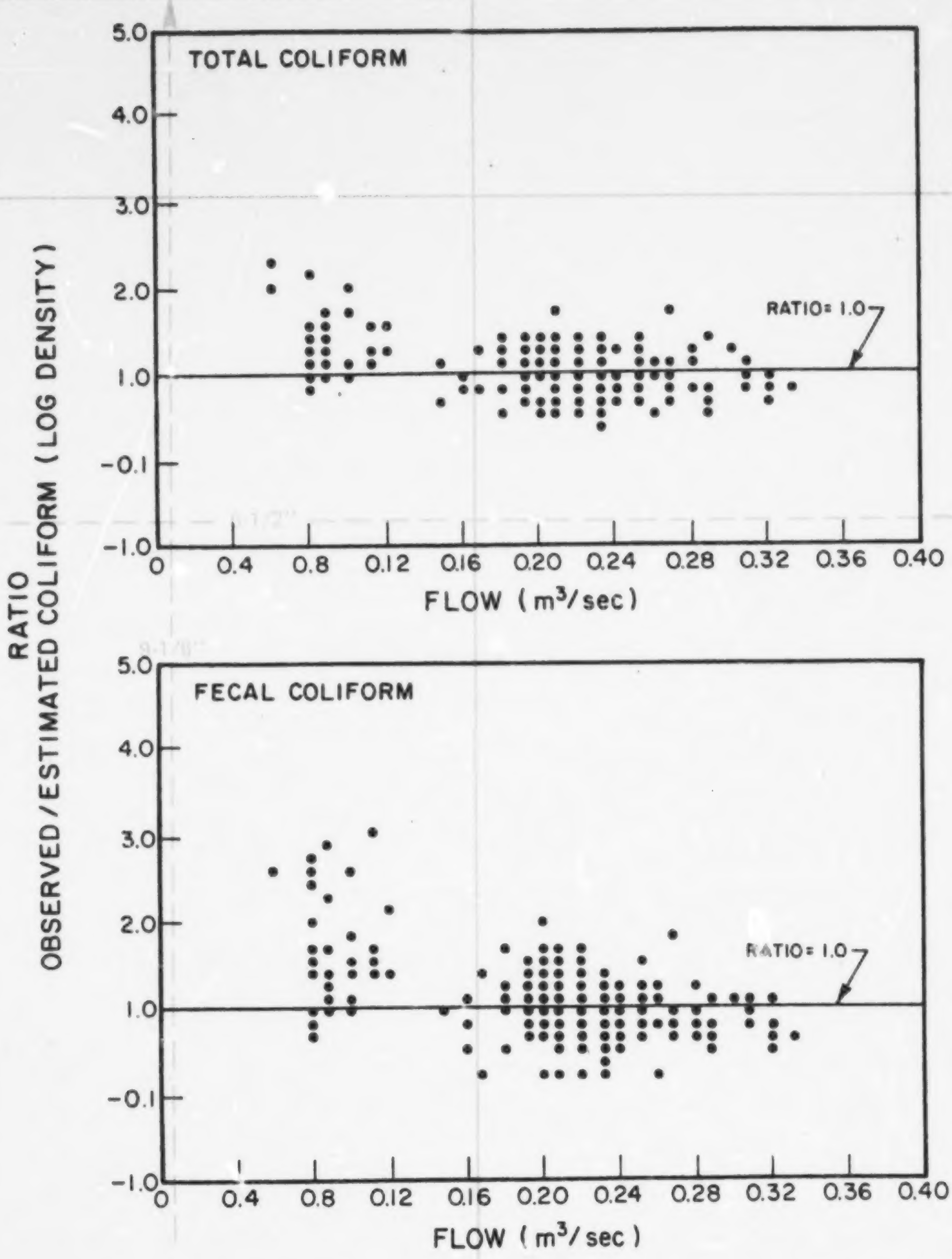

Figure 25. Residual analysis showing significance of flow to dose-response expression

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Table 10 summarizes the results of this 4 month study. Note that approximately 1 week of data was eliminated from this record. These had been obtained during a period of deliberate wiper shutdown, which will be discussed in a later section. As shown on Table 10, the average flow was 0.2 m^3/sec, which represented an average exposure time of 2.23 seconds. The average dose was 130,000 μW-sec/cm^2. The average absorbance coefficient was 0.4 cm^{-1} which is similar to the overall 13-month average of 0.39 cm^{-1}.

Figure 26 is a chronologic record of the influent and effluent fecal coliform density and the applied dose. The mean effluent fecal coliform density was 28 MPN/100 ml for the 4 month record of approximately 70 samplings. A continuous record of these 70 samplings was constructed to estimate the maximum 30-day and 7-day means. As presented on Table 10, the maximum 30-day and 7-day mean fecal coliform densities were 61 and 95 MPN/100 ml, which fall well within the stated criteria. Thus under wastewater conditions which were typical of the full term study, the system demonstrated effective coliform kill efficiency and was able to meet standard effluent coliform criteria.

OPERATIONAL AND MAINTENANCE ASPECTS OF THE U.V. SYSTEM

The ultraviolet system was continually monitored during this study not only to investigate the germicidal efficiency of ultraviolet radiation, but also to evaluate the physical performance of the system under long term operation. Of particular concern was the system's durability, it's maintenance needs, and its ability to operate for long periods without shutdown. It must be understood that the system was a prototype unit and as such susceptible to unanticipated operational problems. Additionally, the 13 month study period does not constitute a long enough test period to evaluate all aspects of system endurance and design. The discussions which follow relate to the observations and data gathered as part of the study of the U.V. system O & M requirements.

U.V. Unit Installation

The installation at NW Bergen was not intended to be permanent. The concept of retrofitting the system to existing chlorine contact chambers was found to be very appropriate, however, and is an ideal application for converting existing plants to ultraviolet light disinfection. The installation of the lamp battery will cause a headloss; at NW Bergen this was found to be approximately 17 cm at a typical flow of 0.295 m^3/sec (See Figure 5). This headloss must be compatible with plant hydraulics in order that a retrofitting application be successful.

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TABLE 10

SUMMARY OF LONG-TERM STEADY STATE EVALUATION

(OCTOBER 1978 - JANUARY 1979)(1)

Parameter	Mean	Range (Min-Max)	Standard Deviation
Flow (m^3/sec)	0.22	0.103-0.283	0.037
Exposure Time (sec.)	2.23	1.73 -4.76	0.45
Dose (μW-sec/cm^2)	130,000	78000-250000	37000
Absorbance Coefficient (cm^{-1})	0.4	0.14-0.56	0.1
Influent Total Coliform (MPN/100 ml)	240,000	4,900-5,370,000	-
Effluent Total Coliform (MPN/100 ml)	109	11-2,400	-
Influent Fecal Coliform (MPN/100 ml)	71,000	2,100-2,400,000	-
Effluent Fecal Coliform (MPN/100 ml)	28	2-240	-

Maximum 30-day Mean - Effluent Fecal Coliform = 61 MPN/100 ml
Maximum 7-day Mean - Effluent Fecal Coliform = 95 MPN/100 ml

(1) Approximately 70 samplings.

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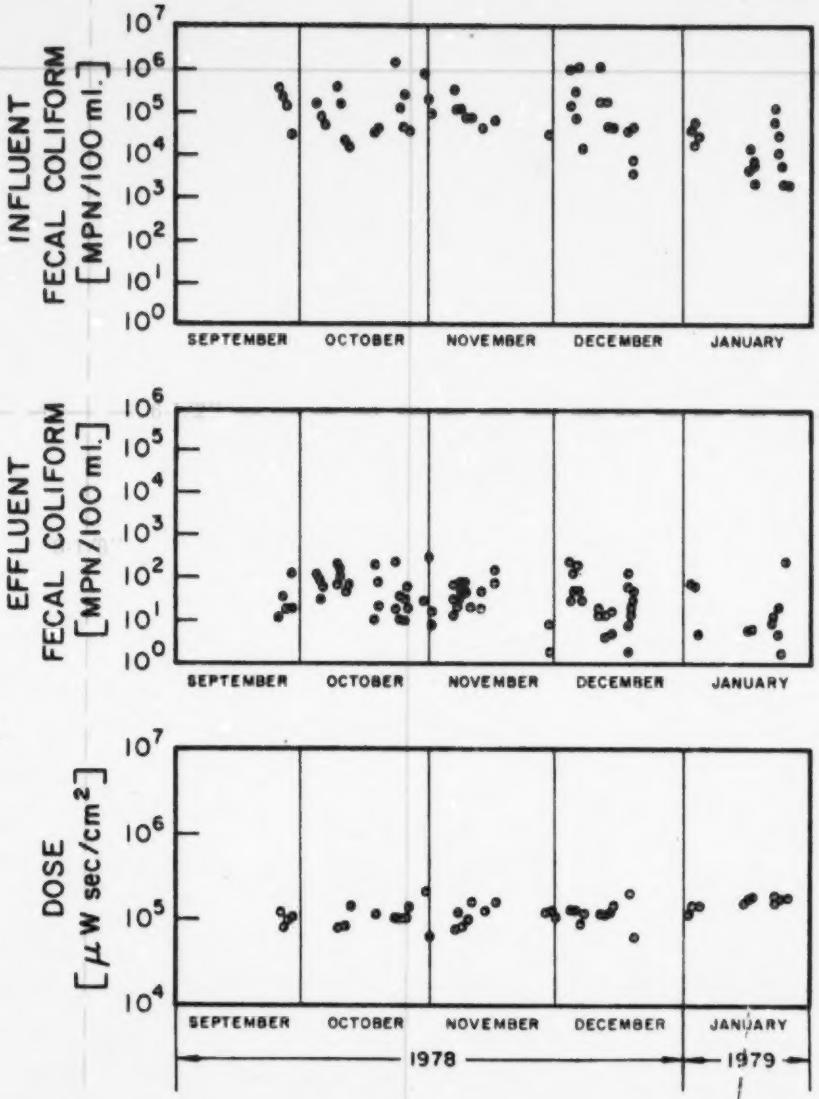

Figure 26. Chronologic record of long-term evaluation.

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Generally, the system operation was found to be very flexible and the system response to changes in operational modes was rapid. The response to changes in the applied voltage was immediate. More time was required to reach stable operation when lamp operation was varied, since a warm-up time is required for the lamps. Any changes in the influent gate valve setting affected the flow through the lamp battery within seconds. More time was required for steady state to be reached at the flow meter. In all, at least ten minutes was allowed prior to sampling at a new U.V. system operational mode.

Several problems were experienced with the pilot unit installation which resulted from the lack of features which would be incorporated into a permanent installation. The unit was not housed in a permanent structure. A series of tarps were positioned around the unit which provided modest protection, but did not adequately safeguard against extreme weather conditions such as heavy rains. This would result in minor problems with electrical shorts. At NW Bergen, heavy rains on October 1, 1978, caused shorting out of one current phase for a period of several days.

A dry well was maintained beneath the U.V. chamber with a sump pump. The pump malfunctioned on two occasions, causing a back-siphoning and eventual flooding of the lamp battery. This problem could be eliminated in the design of a new installation and could be minimized in retrofitted installations through better control, and the installation of back-up systems.

Pre-screening may be required in a permanent installation to prevent an accumulation of fibrous material in the unit, and to prevent lamp breakage from debris that might inadvertantly be present in the disinfection influent channel. At the Northwest Bergen installation, algae would slough from the walls of the secondary clarifiers and would drift to the ultraviolet system as fibrous clumps. These would catch on the quartz sleeves and be swept to the sides by the automatic wiper mechanism. During a high bloom period in September, 1978, such accumulations caused significant quartz sleeve and lamp breakage.

U.V. Unit Operations and Downtime

Table A-1 in Appendix A presents a summary of the operational modes and major maintenance problems and tasks associated with the unit for each day of the field study. The descriptions are necessarily brief but do provide a good indication of the overall unit operations performance for the term of study.

The period of the field study extended from March 6, 1978 to April 18, 1979, a total of 409 days. The system was down for approximately 68 of these days, representing approximately 17% of the study period. Taken at face value, this is a high

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downtime rate. However, a major fraction of this downtime was related to modifying a prototype unit and to the problems of a temporary installation, as discussed earlier. These would not be associated with permanent installations or a fully developed unit, and actual downtime rates would be considerably less than experienced during this study. The major downtime periods are summarized as follows:

March 13-19 (7 days); the system was down due to mechanical problems with the wiper assembly. Once corrected, the assembly was trouble free for the remainder of the study. The only other problem with the wiper mechanism was freezing of the air line feeding the pneumatic cylinder. This caused the wiper to stop on a number of occasions during the winter months (see Table A-1). This would not be a problem in a permanent installation.

March 25-29 (5 days); the dry well flooded and caused shorting and burning of the electrical harness. Again, such an incident can be prevented in the design of a permanent installation.

April 1-9 (8 days); a major electrical short resulted in extensive damage to the unit. One hundred lamps needed to be replaced as a result of this occurrence. The short was caused by a breakdown in the insulation of the original vinyl coated wiring. Despite it's rating, the wiring was found to be inappropriate for a U.V. application. The vinyl wiring was replaced with teflon coated wire which had a rating of 1,000V. This design modification would be incorporated into succeeding systems.

May 22-27 (6 days); problems occurred with the amphenol end caps on the germicidal lamps. This is discussed in more detail in a later section; suffice it to say, that a modification in the lamp design will minimize this problem.

September 6-23 (17 days); this was a major downtime period caused by an accumulation of algae in the lamp battery, as discussed earlier. A prescreening mechanism would prevent the entry of fibrous material into the lamp battery; if allowed to enter, it catches on the quartz and is swept to the ends of the wiper. As it is accumulated, the packing builds the pressure on the quartz, which eventually cracks and requires replacement.

January 6-11 (6 days); the dry well flooded a second time.

February 25 - March 3 (7 days); the system was shutdown in this case to inventory each of the 400 lamps as to operability and U.V. output. Eighty lamps were replaced. This period was of such length due to the experimental study requirements.

Thus, of the 68 days downtime, 56 days are attributed to conditions unique to the field installation and developmental problems in the prototype system. This reduces the downtime rate to approximately 3%. Based on experience with the U.V. system at NW Bergen a downtime of 5-10 days would be anticipated for major full scale applications. Refinement of these estimates can only be made as experience is gained with long-term operation at permanent installations.

System Monitoring

The relative U.V. intensity was measured on approximately twenty lamps at each sampling. The relation of the average measured intensity reading to the theoretical incident intensity at a single lamp surface had been presented earlier in Figure 7. The intensity, as had been discussed in Section 6, is a measure of the applied power over the surface area of exposure. The theoretical incident intensity is based on a calculation of the power output per lamp (derived from the applied voltage and live current) and the exposed surface area of the quartz tube. Since it was impossible, by current U.V. metering standards, to directly measure the actual U.V. intensity within the system, the intensity measurements taken during the study were utilized only as a monitor of lamp U.V. output and quartz clarity.

The nominal power rating of each lamp was 85 Watts. During the early stage of lamp life the actual power output will be 10 to 15% higher than its nominal rating, slowly declining to levels at or below the nominal rating. Figure 27 presents a chronologic record of power/lamp readings taken at full applied voltage. The total power output of the system was divided by the number of lamps engaged to obtain this reading. There is considerable scatter due to uncertainties which existed as to the actual number of lamps in operation. As shown, the power per lamp readings decrease from between 90-100 Watts/lamp in June, 1978, to between 75 and 85 Watts/lamp in March, 1979. The lower display on Figure 27 presents the relative U.V. intensity readings taken during this period. The same trend is shown; in June the readings were between 95,000 and 100,000, and slowly declined to between 80,000 and 90,000 in March, 1979. The lower readings in February were due to problems with the wiper mechanism. The compressed air line was freezing, causing the wiper to stop for periods of time.

Generally, it was determined that both readings (power per lamp, and relative intensity) were useful system monitors and should be used in conjunction with one another. If the intensity readings are decreasing while the power per lamp is

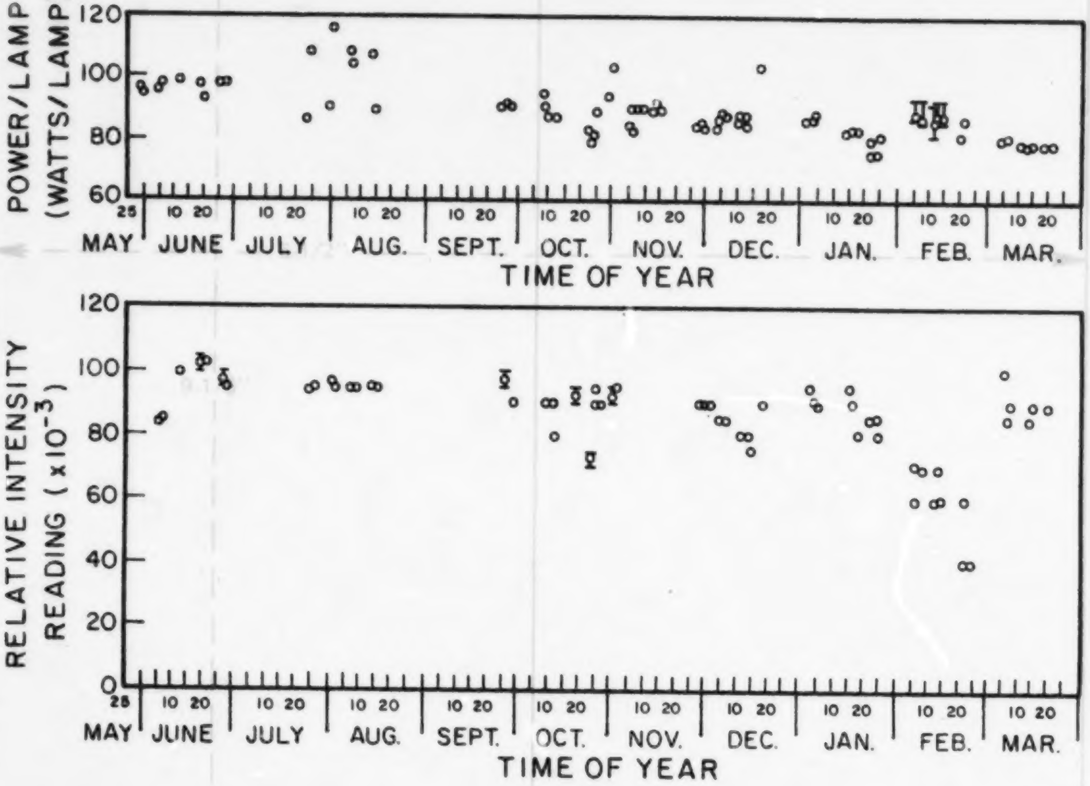

Figure 27. Chronologic record of power/lamp and relative intensity readings.

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still relatively high, it is a signal of quartz surface fouling. If the power per lamp is also decreasing, the lamps may be reaching the end of their useful life.

Incandescent type pilot lights were used to monitor the number of germicidal lamps operating. Very often, however, it was found that the pilot light would be out while the germicidal lamp was still on. Because of the short service lives of the incandescent-type pilot lights, they were not considered an effective monitor of germicidal lamp operability. As an alternate, each lamp was inventoried by direct current readings, typically on a bi-weekly basis. This was time consuming, and should not be considered a routine operations procedure. On March 3, 1978, light emitting diodes (L.E.D.) were substituted in ten positions and found to have excellent service life. Based on this observation, a system of L.E.D.'s to monitor the lamps is recommended for permanent installations.

Germicidal Lamps

The germicidal lamps which were part of the original lamp battery installation were engaged for 6,900 to 7,300 hours (Bank F with least hours, Bank A with most hours of operation). The average number of cold starts for all lamp banks was 56 times in the 13 month study, or about one start for every 125 hours of operation. A summary of lamp replacement thru the term of the project is as follows:

Date	Number Replaced
4/1/78	100
4/20/78	16
5/12/78	23
9/7/78	39
10/16/78	58
11/17/78	43
11/28/78	3
12/6/78	6
12/28/78	4
1/6/79	38
3/3/79	100

Those replaced in March 1979 had deteriorated significantly in U.V. output, thus signalling the end of the life of the lamp. The remaining 330 lamp failures were generally due to a mechanical failure of the plastic end cap on the lamp. The production of ozone by the lamps would cause deterioration of the plastic end caps, allowing moisture to enter, which then resulted in electrical damage to the lamps. A modified lamp design was tested on a limited number of lamps, starting in January 1979, which incorporated molded ceramic end caps. These were apparently resistant to U.V. and ozone, although only approximately 4 months operation was observed as part of this project.

Lamp manufacturers report lamp life in the order of 7,500 hours, assuming a cold start every 8 hours. Based on this fact and the observed lamp endurance record of approximately 7,000 hours, a lamp replacement cycle of 9 to 10 months is suggested. Ten of the 25 lamp ballasts were replaced during the program, due primarily to electrical insulation problems. Manufacturers generally quote a 4-5 year life. A replacement cycle of 4 years is suggested.

Wiper Mechanism

The wiper mechanism operated almost continuously throughout the study period, and was interrupted only during a specific wiper evaluation study, and intermittently through the winter when the air line powering the wiper drive cylinder became clogged with frozen condensation.

A study was conducted in November, 1978, to evaluate the cleaning efficiency of the wiper mechanism. The wiper was shut down while the lamp battery was monitored for quartz clarity and bactericidal efficiency. Figure 28 summarizes the results of this evaluation. Background measurements made prior to shutdown of the wiper indicated an average relative intensity reading (33 lamps) of 95,000. The unit setting was at 100% lamp utilization and 100% applied voltage. The average flow was 0.206 m^3/sec. Effluent coliform densities are shown for October 30 and November 1 to indicate levels representative of this unit mode with the wipers operable.

The wipers were shut down on November 6. The relative U.V. intensity readings decreased within 24 hours to approximately 60% of the initial readings. By the end of the study on November 15, the average relative intensity reading was approximately 35% of the initial reading. The effluent coliform levels did not increase significantly, however, until the eighth day of the wiper shutdown. On November 14, breakthrough occurred, with an effluent total coliform of 660 MPN/100 ml and an effluent fecal coliform of 216 MPN/100 ml. Fecal strep densities are not shown on Figure 28. The background level on November 1 was 59 MPN/100 ml. On November 9, the fecal strep density was 63 MPN/100 ml. Once breakthrough occurred, however, fecal strep also rose to 330 MPN/100 ml.

On November 15th, the wiper mechanism was turned on again. After a few hours operation, samples were taken for coliform and fecal strep density measurements. As shown on Figure 28 the coliform densities returned to levels which were attained prior to the wiper shutdown. The fecal strep density was 90 MPN/100 ml. The relative intensity measurements, however, did not

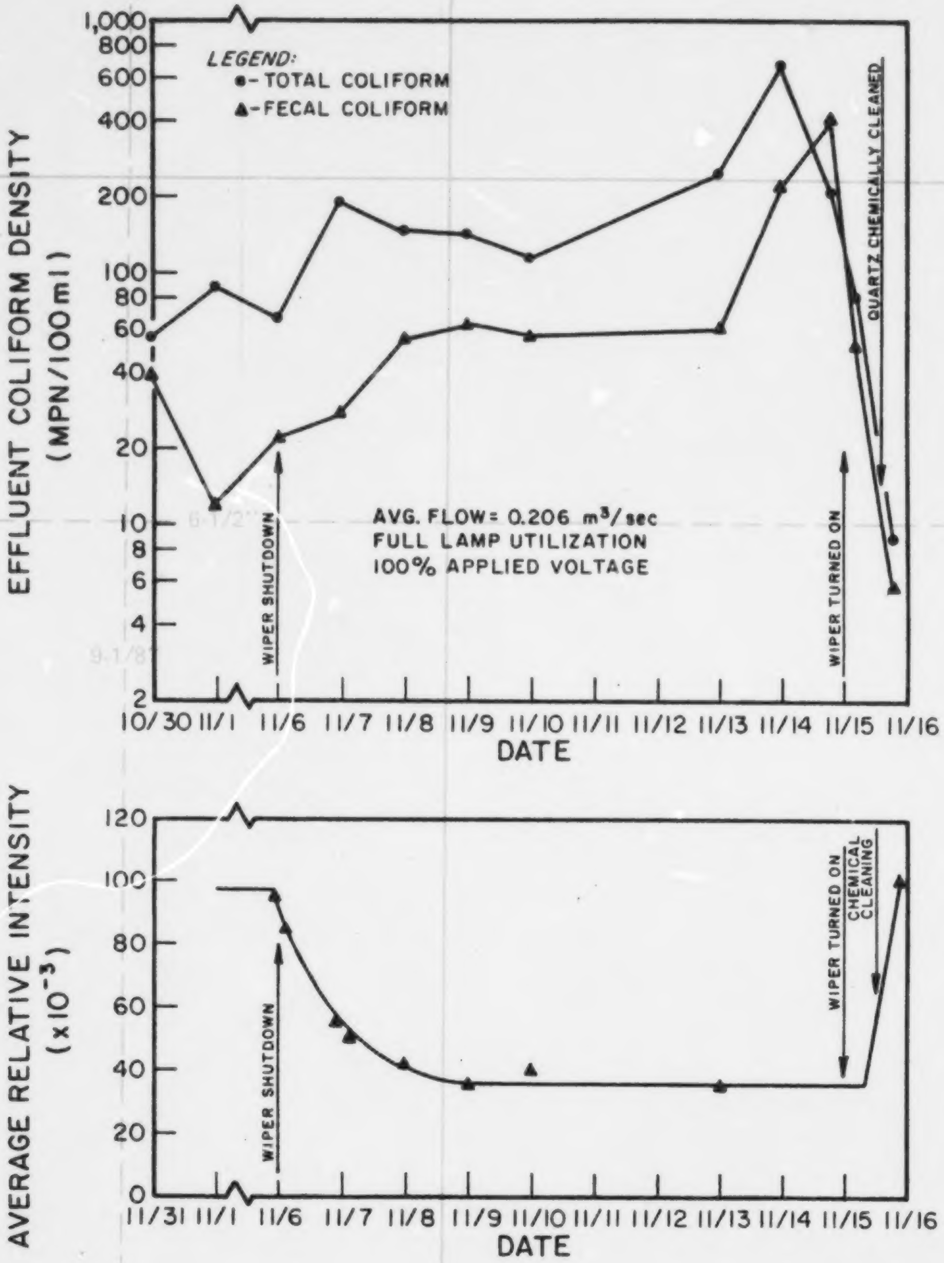

Figure 28. Wiper evaluation: Chronologic record of effluent coliform and relative intensity.

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increase significantly. The wiper mechanism did not appear to be capable of restoring the quartz surface to its original condition once a film was allowed to develop on it.

On November 16 the chamber was drained and the quartz tubes were sprayed with a chemical cleaning solution (Widac), which contained phosphoric acid. Previous to cleaning, the tubes had a heavy film coating the surface, more so on the tubes on the effluent side than on the influent side of the lamp battery. The cleaner was very effective, immediately dissolving the film. The battery was then rinsed with plant recycle water. The cleaning process was complete within one hour (excluding draining and filling the chamber). The average relative intensity reading was 100,000 after cleaning, equivalent to that prior to wiper shutdown. The effluent coliform densities were also significantly lower, as shown in Figure 28.

Post-Field Study Unit Inspection

Upon completion of the field study, the intention was to conduct a detailed inspection of the U.V. system. This was to be performed in conjunction with Pure Water Systems and was to provide information on system wear. Stating the proprietary nature of work being conducted at the PWS facility in Fairfield Lawn, Pure Water Systems did not allow HydroQual (formerly Hydroscience) personnel to observe the dismantling and inspection of the U.V. unit. The following is a synopsis of the PWS report submitted to HydroQual (36).

(1) No breakage or scratching was observed on any of the quartz tubes.

(2) The wiper gland wear ranged from 0.051 mm to 0.254 mm. In some cases this wear resulted in a clearance between the lamp and the wiper gland (99 lamps had a clearance of at least 0.025 mm, while 54 had clearance of at least 0.10 mm between the quartz and the wiper gland), and in these cases the quartz tubes were coated with a film. Torn lips were observed on 28 of the 400 wiper glands.

(3) The wiper actuator cable diameter decreased by as much as 1.02 mm where the nylon sheath was exposed to the U.V. radiation. The diameter reduction resulted in air leakage at the wiper cylinder seals and water leakage at both end plate seals of the U.V. unit. However, the leakage did not affect the wiper operation.

(4) There was no detectable wear on the wiper guide rails or the mating linear bearings.

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(5) No leakage of the quartz jacket seals was observed, and no deterioration of the seal rings was detected.

(6) Ten of the 25 ballasts were replaced during the program. The most common reason for failure was from an insulation breakdown on the wire leads running from the ballasts. Teflon covered wiring was suggested for future installations.

(7) Corrosion was observed only on the aluminum seal adaptors at the influent-effluent baffle plates. No corrosion was observed on the main structure of the U.V. unit, wiper plate, quartz seal glands, cable retainer or wiper guide and support.

SECTION 8

PHOTOREACTIVATION

The lethal and damaging effects of ultraviolet light on bacterial cells are the result of absorption of ultraviolet energy by the cell's genetic material, deoxyribonucleic acid, or DNA. The damage incurred by this absorption is the dimerization of thymine, one of the basic components of DNA. This dimerization, if not too extensive, can be reversed in some microorganisms by subsequent exposure of the irradiated cell to a variety of energy wavelengths in the visible light range of approximately 310 to 500 nm. This phenomenon is called photoreactivation.

REPAIR MECHANISMS

Several investigators have noted that ultraviolet induced mutations and death are only irreversibly fixed after a significant delay in time, during which there is an increase in cell viability (37,38,39). The mechanisms of repair from the damage induced by ultraviolet light have been studied in depth, especially in strains of Escherichia coli. Three major enzyme repair mechanisms known to operate are as follows:

Photoreactivating Enzyme (PRE): The enzyme binds pyrimidine dimers in the DNA. The binding can occur in the dark, but it requires light in the 310nm-400nm range to monomerize the dimers. Photoenzymatic repair is the most common and usually the most effective repair mechanism.

Dark Repair: Pyrimidine dimers are not split as in photoreactivation, but they are removed from the DNA by a multienzymatic mechanism termed excision repair. The distortion of the double helix caused by the dimer is recognized by an enzyme which nicks the dimer from the DNA strand on one side. An exonuclease then releases the dimer completely from the DNA strand. A replicating DNA enzyme then repairs this gap.

Dark Post Replication Repair: This mechanism has been shown to occur in growth supporting media. Pyrimidine dimers that are not removed block the continuous progression of DNA replicating enzymes. This results in daughter strands with gaps of about 1,000 nucleatides long. Post replication repair enzymes repair these strands (40).

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The wild type *E. coli* has been found capable of repairing as many as 1,000 pyrimidine dimers by one or all of the above mechanisms (40). The mechanisms in *E. coli* have been studied to the point where specific genes and gene products have been shown to be responsible. More so than dark repair, the photoreactivation mechanism (PR) seems to result in a dramatic increase of cell viability in time ranges in the order of minutes.

PHOTOREACTIVATION MECHANISM

Light as a factor in ultraviolet irradiation recovery of bacteria and bacteriophages was first elucidated in 1949 by Kelner and Dulbecco, respectively. *Streptomyces griseus* spores which were irradiated and subsequently exposed to visible light showed an increase in viability 100,000-400,000 times, whereas ultraviolet irradiated cells that were placed in the dark showed little recovery. Non-ultraviolet treated cells placed in the light were not significantly affected (38). Dulbecco showed that irradiated phage (bacterial virus) mixed with unirradiated host bacteria, and left exposed to fluorescent light for a period of time, formed a greater number of plaques (a measure of viability of the phage) than when not exposed to visible light (37).

Subsequently, this photoreactivating effect was seen in cells of many organisms, including viruses and phages (if in host cell), bacteria, algae, fungi, higher plants, protozoa, echinoderms, arthropods, and invertebrates, except the placental mammals (41). Among the microbial organisms, photoreactivation has been shown to occur in *Streptyomyces*, *E. coli*, *Saccharomyces*, *Aerobacter*, *Micrococcus*, *Erwinia*, *Proteus*, *Pencillium*, and *Neurospora* (42). Bacteria in which photoreactivation has not been found to occur include *Haemophilus influenzae*, *Diplococcus pneumoniae*, *Bacillus subtilus*, and *Micrococcus radiodurans* (41).

Environmental Conditions Affecting Cellular Repair of Ultraviolet Damage

Environmental conditions (such as low temperature or low nutrient levels) which tend to inhibit active cell metabolism (with the exception of repair) and cell division for a time after exposure, decrease the lethal and mutagenic effects of the ultraviolet radiation (43). The inhibiting conditions allow time for the cell to repair its DNA before it is erroneously and, perhaps, lethally replicated for a daughter cell or before the cell attempts to produce some necessary protein which may be defective due to erroneous RNA coding products caused by a defective DNA template (39,44,45).

Many researchers' observations on whole cell systems have supported this theory. Of course, light is essential for photoreactivation, but its effect, as well as that of dark repair,

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is affected by other environmental conditions. Environmental conditions influence the growth rate of the population. A population in its lag or stationary growth stage will have a greater chance of recovery because, by definition, it is not replicating its DNA as quickly as an exponentially growing population. The recovery of irradiated phage is also dependent on the physiological condition of its host cells (37).

Other investigators have reported similar effects from non-nutrient buffers of minimal media. In one experiment, E. coli B cells (irradiated by ultraviolet doses resulting in 0.1-65% survival), showed a greater dark repair recovery in a minimal synthetic medium than when inoculated into a nutrient rich complex medium. The effect was most likely due to the synthetic medium extending the lag phase of the culture from 0.5 h to 3 h (46). A similar effect has been reported by others (42,43). In addition, a lower temperature tends to increase lag time and, thus recovery (42).

A variety of other conditions, all apparently affecting the cell's metabolic activity and growth rates, affect recovery. Compounds which specifically inhibit new DNA synthesis increase the length of time for recovery after ultraviolet exposure (39). Anaerobically grown cells of E. coli have been found more resistant than aerobically grown cells to ultraviolet, possibly because the anaerobic growth rate is slower than the aerobic rate (39). Exposure to antioxidants such as alcohol, glycol, and thiols before and during ultraviolet exposure is also effective in increasing recovery (47).

Indirect Light Effects

Besides photoreactivation, other interactions of light occur with ultraviolet irradiated cells. Photoprotection occurs when cells are exposed to wavelengths of about 334 nm prior to ultraviolet exposure. Here, damaged quinones may possibly inhibit growth allowing for more complete dark or light repair (43). Photoprotection has been observed in E. coli B and Pseudomonas (41,43). A higher dosage of light is required for photoprotection than for photoreactivation. The mechanism is independent of photoreactivation since cells containing no PRE enzyme can be photoprotected (41).

Exposure to high intensity light of wavelengths greater than 310 nm have more lethal, than mutagenic effects. These wavelengths are not absorbed by DNA as are ultraviolet, but rather they can cause irreversible damage by peroxide formations that form free radicals, which in turn can oxidize and destroy nucleic acids, proteins, and lipids. Dyes such as methylene blue and rose bengal accelerate this process and result in increased sensitivity to light (48).

PHOTOREACTIVATION STUDIES AT NW BERGEN

Photoreactivation is an important phenomenon and must be considered when applying the ultraviolet light process to the disinfection of municipal treatment plant effluents. Recent studies have confirmed the activity of photoreactivation in such applications (22,26). Environmental conditions in a secondary effluent would appear to be similar to those that are conducive for both photoreactivation and even dark repair of ultraviolet damage in pure cultures. Nutrient levels are relatively low, and the organisms are usually in the stationary growth phase at the time of ultraviolet exposure.

In an experiment performed by Kelner on Streptomyces griseus spores, U.V. irradiated suspensions could be kept at refrigerator temperatures in the dark for up to 4 hours without interfering with subsequent photoreactivating recovery (38). Thus, an effluent treated and discharged at night might exhibit photoreactivated recovery the next morning in addition to dark repair.

Many variables are involved in predicting the recovery effect in systems such as a wastewater treatment plant. Sunlight at any one site will differ in intensity and wavelength according to season, time of day, and cloud cover. Penetration of photoreactivating wavelengths through the effluent will depend on the water's physical and chemical characteristics, such as turbidity, solids, organics, etc. Shallow levels in effluent tanks and receiving water would be more conducive to photoreactivation than deeper water levels, depending on mixing conditions.

The more practicable means of minimizing the impact of photoreactivation would be to increase the U.V. dosage to a point beyond the survival curve where photoreactivation effects are much less significant. Keeping the U.V. effluent in the dark for a period of time would not be suitable, since dark repair could occur and photoreactivation may occur in the cells once re-exposed to light. Sequential application of U.V. would probably be no more effective than increasing the U.V. dosage in one application. Manipulating the microbial populations into the more sensitive logarithmic state for U.V. disinfection would be complicated and probably undesirable.

A significant effort was made as part of the NW Bergen study to assess the impact of photoreactivation. The analysis procedures were directed to quantifying the extent of photoreactivation rather than the mechanisms of repair, in line with the practical applications aspect of the field study. These tests were outlined in Section 5. The standard procedure, known as the static bottle test, relied on comparing post U.V. irradiation dark survival of cells with cell survival subsequent

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to exposure to photoreactivating light (in this case, sunlight). A second approach utilized the dynamic conditions of the contact chamber. Photoreactivation was quantified in this case as the difference in coliform density immediately following the ultraviolet disinfection unit (zero exposure time to photoreactivating light) and a point downstream.

Photoreactivation as a Function of Exposure Time

On May 30, 1978, a study was performed to determine the degree of repair as a function of time of exposure to photoreactivating light (sunlight). The objective of this exercise was to determine a standard exposure period for subsequent static tests.

Samples were taken after irradiation at two dosage levels, 380,000 μW-sec/cm^2 and 57,000 μW-sec/cm^2. The irradiated samples were inoculated immediately for coliform density analysis, and aliquots were placed in two sets of borosilicate bottles; one set was transparent to light while the second set was shielded, or dark. The bottles were submerged in a water bath to maintain a constant temperature.

The light and dark bottle aliquots of the irradiated samples were measured at exposure intervals of 10, 30, 90, and 180 minutes. The results are presented on Figure 29. At a dose of 380,000 μW-sec/cm^2, which with subsequent experience was found to be extremely high, the fecal coliform densities were less than 20 MPN/100 ml in both the light bottle and dark bottle aliquots (except for the light at 10 minutes), which was the minimum detection level in this case. Thus at the higher dosage condition, there could be no differentiation between the light and dark samples. The total coliform density was found to increase significantly after exposure to light with a peak reading at 90 minutes.

At the lower dosage level, the fecal coliform population exposed to light increased immediately and appeared to level off after 30 minutes. The dark sample decreased in density through 90 minutes, but exhibited an apparent increase after 180 minutes. The total coliform exhibited responses similar to the fecal coliform at this dosage level. Based on the results of this analysis, a 60 minute sunlight exposure time was selected as an appropriate interval to assess the degree of photoreactivation at various dosage levels.

Comparative Analysis: Dynamic and Static Procedures

The primary procedure employed during this study to evaluate photoreactivation was the static bottle test. An analysis of the results derived from these tests is presented in a later section. The test is felt to be an effective and practical

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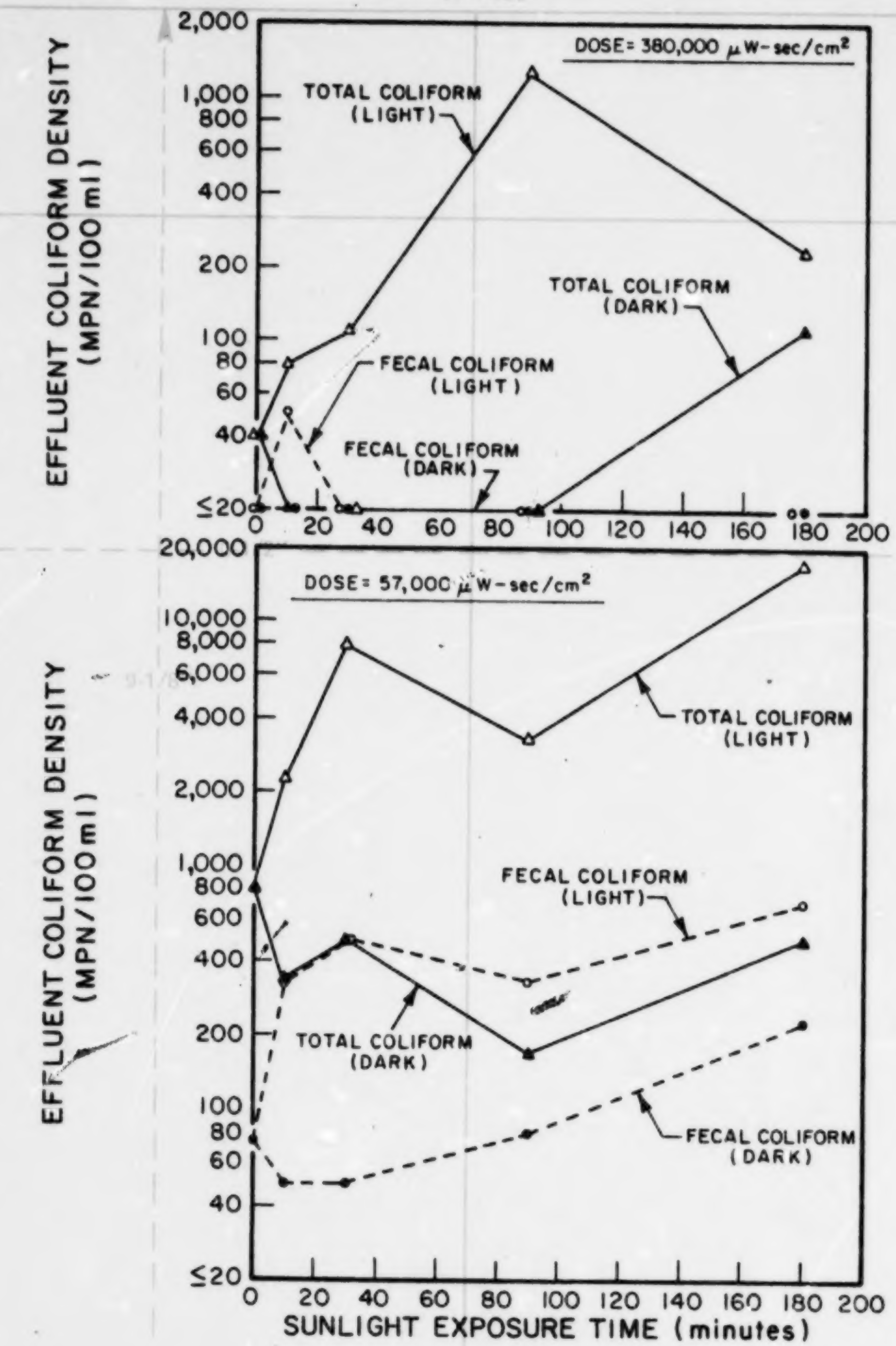

Figure 29. Photoreactivation as a function of sunlight exposure time.

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bioassay procedure which provides a reasonable approximation of the kinetics associated with photoreactivation on a receiving water. The test is relatively simple and offers the benefit of being controllable under standard test conditions. This can allow comparative analyses with the results of other investigations.

An alternative procedure was used, on occasion, which was based on an in-situ analysis of photoreactivation. The presence of the long chlorine contact chamber following the U.V. unit prompted the suggestion that it would provide an ideal site to simulate stream conditions. This so-called dynamic test involved sampling at preselected locations in the chamber (typically a short distance upstream of the effluent weir) and comparing the coliform densities to those measured immediately after irradiation. The time of exposure to photoreactivating light was computed as the time of travel (theoretical) to the specified location in the contact chamber.

On July 10 and 11, 1978, dynamic tests were conducted; static samples were also monitored for comparison. Prior to sampling, the flow through the U.V. unit was stabilized at a selected level to provide a total detention time of one hour, and the chlorine flow to the diffuser downstream of the U.V. unit was stopped. These conditions were maintained for several hours (16 - 24 hours) to allow the system to reach steady state operation.

The results of the study are presented on Figure 30. The channel samples exhibited a marked increase in both total and fecal coliform density with increasing time of exposure to sunlight. The total coliform increased from a post irradiated average density of 740 MPN/100 ml to 6,100 MPN/100 ml at 30 minutes, and 11,500 MPN/100 ml at 60 minutes. The fecal coliform density averaged 320 MPN/100 ml after irradiation and increased to 1,500 MPN/100 ml after 30 minutes and to 1,700 MPN/100 ml after 60 minutes exposure to sunlight. The static bottle tests results are also shown for comparison. The dark bottle densities increased for both total and fecal coliform. The increases exhibited in the light bottles were significantly higher than the dark bottles. The increase in the light bottle total coliform was similar to that exhibited by the total coliform in the channel sample. The density increase by the fecal coliform, however, was significantly higher than that measured in the channel.

Dynamic and static tests were again conducted on October 19, 1978, at a dose of 150,000 μW-sec/cm^2 and October 31, 1978, at a dose of 70,000 μW-sec/cm^2. These results are displayed on Figure 31. At the higher dose, the channel sample showed an increase in both total and fecal coliform density. The concurrent static tests indicated no increase in the dark

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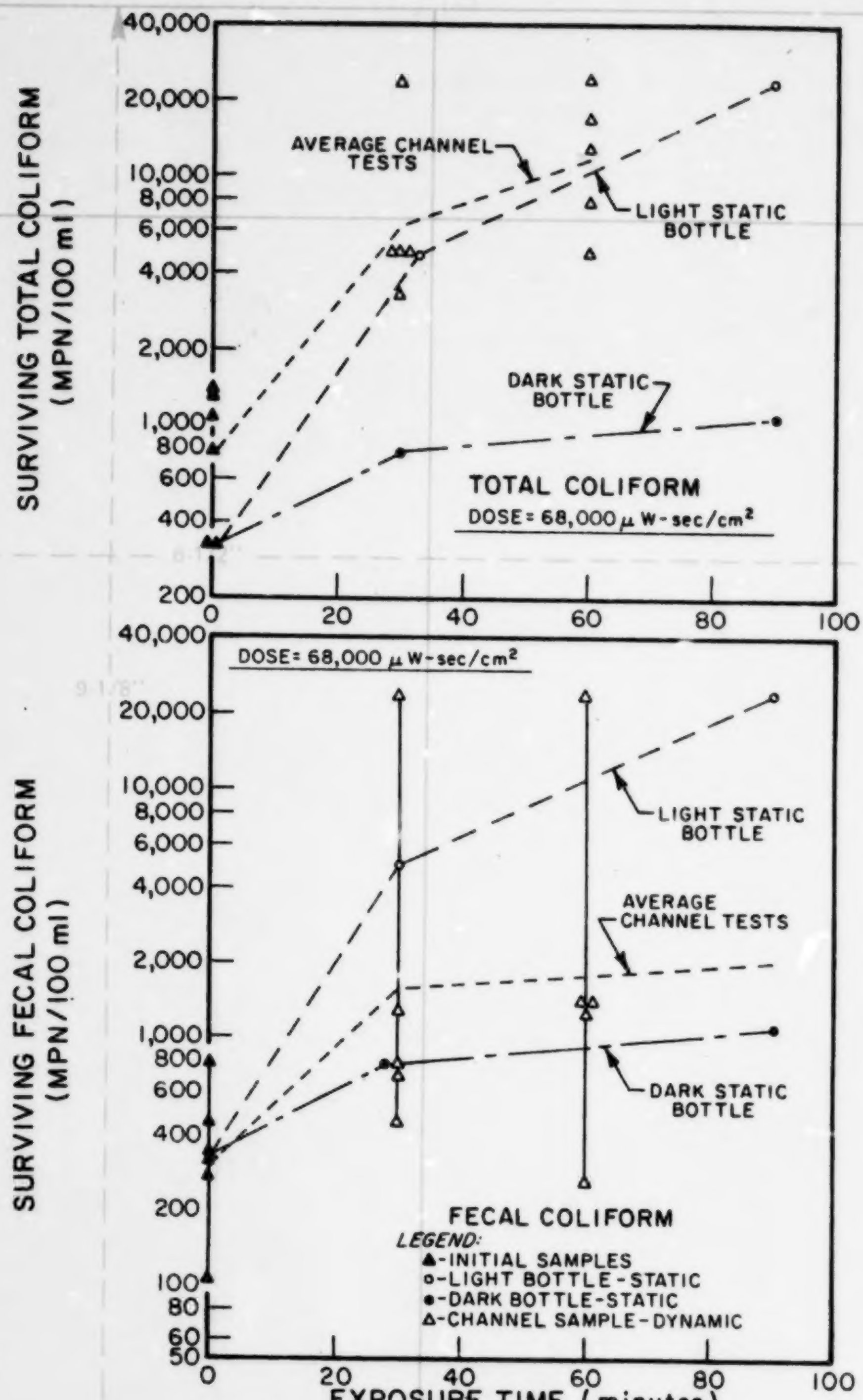

Figure 30. Photoreactivation channel study, July 10-11, 1978

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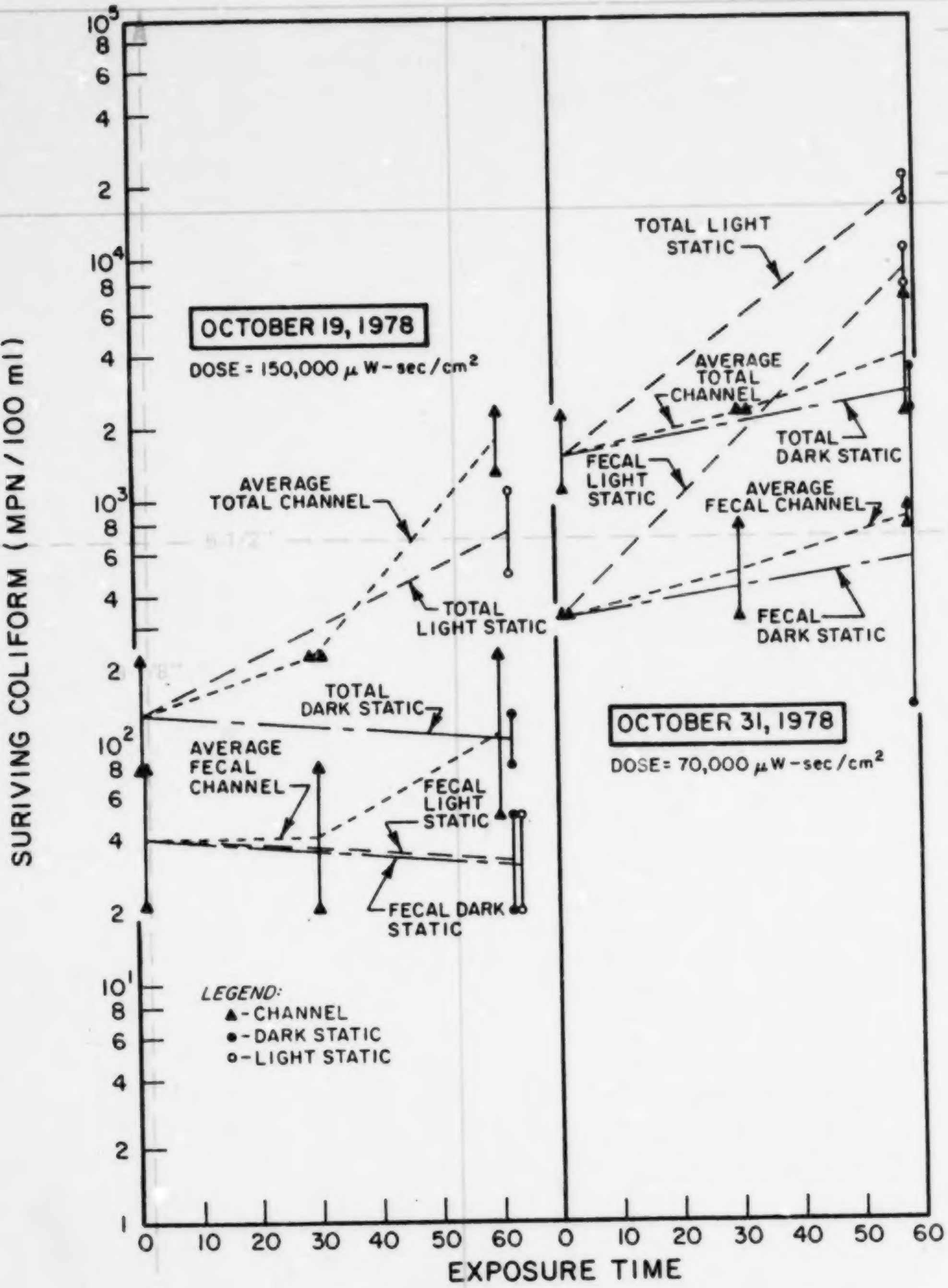

Figure 31. Photoreactivation channel studies, October 19 & 31, 1978

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bottles. There was no change in fecal density in the light bottle, while there was an increase in total coliform density, although less than the increase measured in the channel samples.

At the lower dose level (October 31, 1978), there was an increase in total and fecal coliform density for both the channel test and the static test. The increase was significantly greater in the static test in this case.

On December 18 and 19, 1978, tests were conducted in which aliquots of irradiated effluent samples were placed in light and dark bottles. These were then placed in the channel at various depths for the prescribed exposure period. This modification to the static test procedure was incorporated to evaluate the impact of reducing the sunlight intensity to which the samples are exposed. The bottles were submerged at depths of 0.15 and 1.25 meters and coliform densities were measured after 1 and 3 hours exposure. Channel samples were also taken upstream of the weir two hours after the irradiated effluent sample was drawn and set in the static bottles. Two hours was the calculated detention time in the channel at the flow conditions which existed during the study. Two dose levels were studied; on December 18 the dose was 219,000 μW-sec/cm^2, while on December 19 the dose was 77,000 μW-sec/cm^2. The results are summarized in Table 11.

At the higher dose of 219,000 μW-sec/cm^2 there was little evidence of any significant degree of photoreactivation taking place in either the channel or the static light bottles. There also were no apparent differences in coliform densities measured at the 0.15 m and 1.25 m depths.

Photoreactivation did occur, however, at the lower dose of 77,000 μW-sec/cm^2. Increases which approximated an order of magnitude were measured at the end of the contact channel for both total and fecal coliform. Equivalent increases were noted for the fecal coliform density in light bottle samples held at the 0.15 m depth. There was little evidence of photore-activation at the depth of 1.25 m, suggesting that the wastewater absorbed the photoreactivating energy before it reached the bottle depth.

From February 21 to 23, and April 16 to 18, 1979, intensive photoreactivation studies were conducted to determine if there was a significant difference between densities measured in channel samples and static light bottle samples, which had been exposed for an equivalent time period (channel detention time). The data from these samplings are summarized on Table 12. A "t" test analysis failed to reject (5%) the null hypothesis that there was no significant difference between the coliform levels measured in the static bottle and those measured in the effluent channel.

TABLE 11

PHOTOREACTIVATION STUDIES CONDUCTED DECEMBER 18 AND 19, 1978

December 18, 1978 Dose = 219,000 μW-sec/cm^2

	Total Coliform(1) (MPN/100 ml)	Fecal Coliform(1) (MPN/100 ml)
Irradiated Effluent(2)	212 (4)	20 (4)
Static Light Bottle;		
60 min(3), 0.15 m(4)	328 (2)	77 (2)
1.25 m	123 (2)	4 (2)
180 min, 0.15 m	726 (2)	87 (2)
1.25 m	193 (2)	53 (2)
Static Dark Bottle;		
60 min, 0.15 m	155 (2)	24 (2)
1.25 m	75 (2)	5 (2)
180 min, 0.15 m	378 (2)	51 (2)
1.25 m	700 (1)	7 (1)
Channel Sample; 120 min.	94 (3)	19 (3)

December 19, 1978 Dose = 77,000 μW-sec/cm^2

	Total Coliform(1) (MPN/100 ml)	Fecal Coliform(1) (MPN/100 ml)
Irradiated Effluent	197 (4)	25 (4)
Static Light Bottle;		
60 min, 0.15 m	12,130 (2)	435 (2)
1.25 m	1,269 (2)	24 (2)
180 min, 0.15 m	19,595 (2)	1,177 (2)
1.25 m	2,437 (2)	156 (2)
Static Dark Bottle;		
60 min, 0.15 m	2,900 (2)	202 (2)
1.25 m	470 (2)	10 (2)
180 min, 0.15 m	1,650 (2)	105 (2)
1.25 m	675 (2)	43 (2)
Channel Sample; 120 min.	1,877 (3)	417 (3)

1. ( ) number of samples
2. Zero time of sunlight exposure
3. Exposure to sunlight
4. Depth in Channel

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TABLE 12

SUMMARY OF DATA: COMPARISON OF STATIC LIGHT BOTTLE AND CHANNEL PHOTOREACTIVATION TESTS

	Effluent Coliform in Static Light Bottle (1 hour) (MPN/100 ml)		Effluent Coliform at End of Channel (1 hour) (MPN/100 ml)	
	Total	Fecal	Total	Fecal
2/21-23/79	110	79	460	26
	79	8	170	110
	1,100	110	9,200	1,300
	1,300	49	5,400	1,700
	17,000	490	22,000	3,300
	54,000	4,900	13,000	2,400
	35,000	33,000	35,000	4,600
	35,000	17,000	35,000	3,300
	11,000	1,300	24,000	3,300
	22,000	4,900	160,000	2,400
Mean	3,570	702	9,371	1,000
4/16-17/79	540	17	920	23
	220	17	1,300	110
	240	14	130	33
	1,700	790	1,300	330
	630	110	170	33
	460	79	170	49
	2,200	700	4,900	330
	4,900	1,700	4,900	790
	4,900	125	1,069	177
	968	125	1,069	177

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To summarize, the comparative analysis of the static and dynamic test procedures for measurement of photoreactivation indicates that the static bottle tests present a realistic approximation of the effluent coliform populations subsequent to photoreactivation. The test is controllable, and can be standardized. It also can be manipulated rather easily to vary the parameters of concern, such as temperature. The channel, or dynamic, procedure does not offer these benefits and certainly is not a procedure which can be standardized. In light of these considerations, the results of the static tests were relied upon to assess photoreactivation.

Analysis of Photoreactivation Static Test Results

Static light/dark bottle tests were performed during two periods of the field study. The first period was June 5 through August 15, 1978. Aliquots of 100 of the 119 U.V. irradiated samples drawn for routine analysis were placed in borosilicate bottles, which were then placed in a water bath held at the sampling temperature. The samples were then exposed to natural sunlight conditions for a period of one hour, at which time total and fecal coliform densities were determined.

Approximately 25% of the samples set for the light bottle test were also held for one hour in dark, or opaque, bottles. These served as controls: if no significant differences were noted between the densities in the dark bottles and the densities measured immediately after ultraviolet irradiation, any increase in the light bottle density would be attributed to photoreactivation.

Paired "t" tests were performed, which compared the log total and fecal coliform densities measured in the post-irradiated effluent and the one-hour dark bottle samples. The null hypothesis was that the means of the two samples were equal. The calculated values of t were 1.35 (27 d.f.) for total coliform and 1.81 (20 d.f.) for fecal coliform, as compared to t test values (5% significance) of 2.05 and 2.09, respectivaly. Thus, the test failed to reject the null hypothesis, indicating that there is no significant difference in density measurements made immediately after irradiation and after the sample is held in a dark bottle for one hour. This allowed the interpretation that any measured increase in the light bottle sample density was attributable to photoreactivation.

Static light/dark bottle tests were also performed between February 5 and April 17, 1979. A total of 38 samples were set concurrently with the routine samples. This yielded a total record of 138 samples from which to analyze photoreactivation.

The coliform survival data were analyzed on the basis of a second order relationship. A step-wise multiple regression

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analysis indicated temperature to be significant. The regression equation for total coliform was determined to be,

$$TC_p = (4.0 \times 10^{11})\ 10^{0.07T} D^{-1.86} \qquad (8\text{-}1)$$

where:

TC_p = Post U.V. irradiated total coliform density measured after 1 hour exposure to sunlight (MPN/100 ml)

T = Temperature (°C)

D = Dose (μW-sec/cm^2)

A correlation coefficient of 0.78 was determined, indicating that 60.8% of the coliform variance is explained by the dose level and water temperature. A regression analysis of the photoreactivated data and dosage alone yielded a correlation coefficient of 0.72, indicating that 51.8% of the coliform variance is explainable. Thus a 20% improvement in the regression is made by including temperature as an independent variable.

A multiple regression analysis was also conducted on the density data at zero sunlight exposure time, representing the irradiated effluent samples from which the aliquots were drawn for the photoreactivation static tests. Temperature was not found to be significant (as was the case in the analysis of the total non-photoreactivation data record (Section 7)). The regression equation was determined to be,

$$TC = (8.1 \times 10^{12})\ D^{-2.08} \qquad (8\text{-}2)$$

where:

TC = total coliform density of sample immediately after U.V. irradiation (unexposed to sunlight) (MPN/100 ml)

D = Dose (μW-sec/cm^2)

The photoreactivation data for total coliform are presented in Figure 32. The temperature ranged between 18°C and 24°C for the period of June 5 to August 15, 1978, with an average of 20.7°C. During the second period in which static light/dark tests were performed, February 5 through April 17, the average temperature was 11.2°C, with a range of 9.5 to 14.5°C. Thus there is an average temperature differential of 9.5°C for the two periods.

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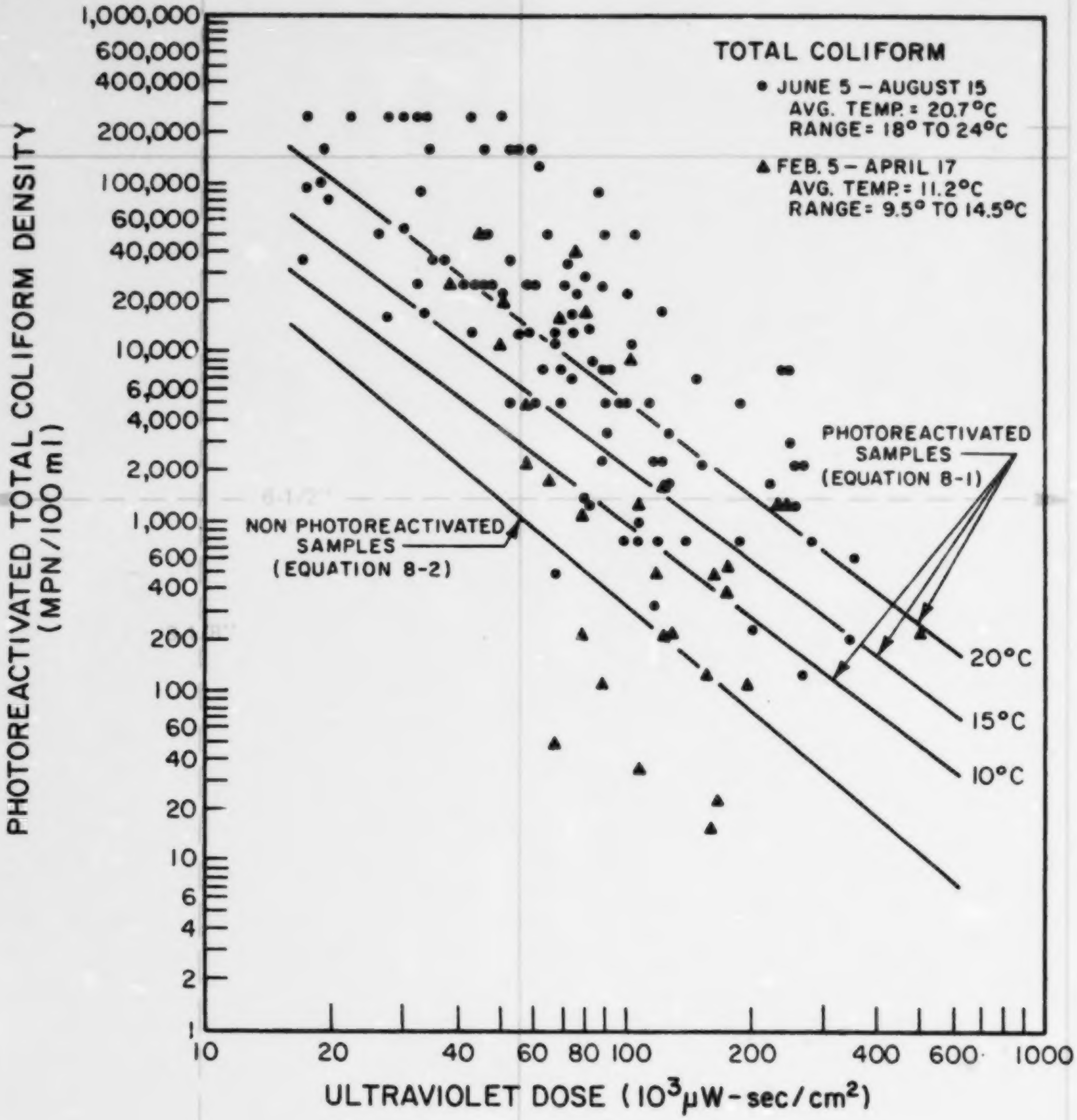

Figure 32. Photoreactivation of total coliform.

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The observed data presented on Figure 32 are the static photoreactivated data only and are differentiated as to the two temperature periods. The regression lines shown are solutions for Equation (8-1) for photoreactivation at 10°C, 15°C, and 20°C. The non-photoreactivation regression line is also shown for comparison (Equation 8-2).

The results of the photoreactivation analyses for fecal coliform are presented in similar fashion on Figure 33. As with total coliform, a step-wise multiple regression analysis indicated a significant dependency of photoreactivation on temperature. The regression equation determined from this analysis is,

$$FC_p = (1.35 \times 10^{13})\ 10^{0.07T} D^{-2.32} \qquad (8\text{-}3)$$

where:

FC_p = Post U.V. irradiated fecal coliform density measured after 1 hour exposure to sunlight (MPN/100 ml)

T = Temperature (°C)

D = Dose (μW-sec/cm^2)

The correlation coefficient was 0.8 (64% of the variance explained). The regression with dosage alone yielded a correlation coefficient of 0.73; this indicated explanation of approximately 53% of the variance associated with the photoreactivated coliform data. Thus, inclusion of temperature as an independent variable allowed a significant improvement in the regression analysis. Again, temperature was not significant in the regression for non-photoreactivated data. The regression equation in this case was,

$$FC = (1.91 \times 10^{12})\ D^{-2.07} \qquad (8\text{-}4)$$

where:

FC = fecal coliform density of sample immediately after U.V. irradiation (unexposed to sunlight) (MPN/100 ml)

D = Dose (μW-sec/cm^2)

At 10°C the regression expressions predict approximately a two-fold increase in fecal coliform density due to photoreactivation. At 20°C, a ten-fold increase is predicted. The implication of photoreactivation is that a higher dosage would

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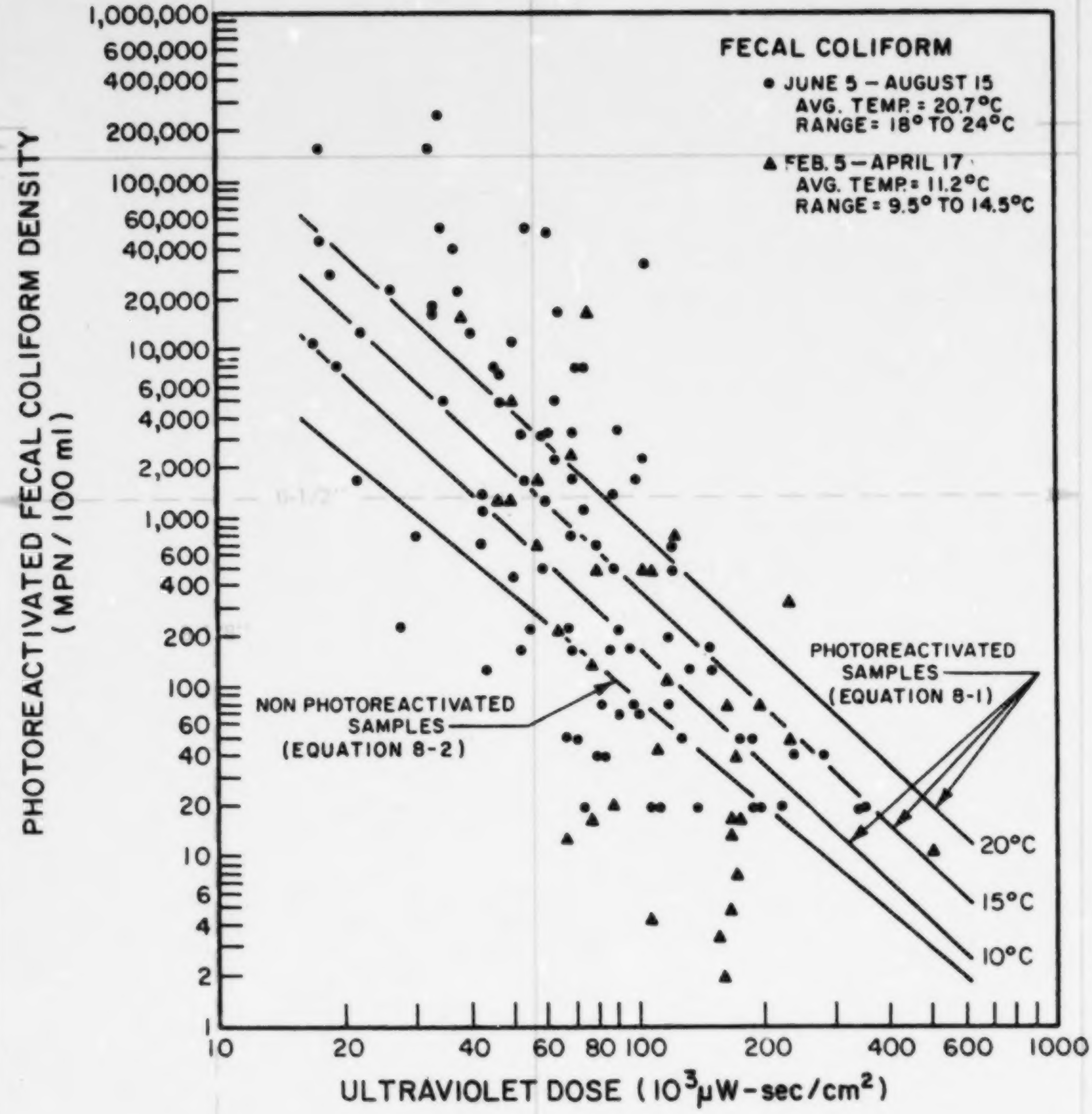

Figure 33. Photoreactivation of fecal coliform.

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be required if photoreactivation were to be accounted for in effluent criteria. Thus, for a required effluent fecal coliform density of 200 MPN/100 ml, a three-fold increase in dosage would would be necessary at 20°C if the impact of photoreactivation were to be considered. This phenomenon of a constant factor density increase due to photoreactivation (or conversely a dose reduction factor) is supported by various studies reported in the literature (41).

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SECTION 9

SYSTEM DESIGN AND COSTS

The results of the NW Bergen field program analysis have been presented in the preceding sections. Dose-response relationships were detailed, as well as observations of the O&M requirements for the U.V. process. Based on these results, a rational design procedure is suggested in the following discussions to size an ultraviolet disinfection system. Several design considerations are also presented which are judged important to the physical design of a U.V. facility.

Finally, engineering cost estimates have been developed from the results of this study. The costs can be used to provide preliminary screening estimates of U.V. system applications relative to alternative disinfection processes.

ULTRAVIOLET DISINFECTION SYSTEM SIZING

Analysis of the U.V. system and the results of the field study allowed the development of a rational design procedure which is based on effluent criteria, plant effluent characteristics, and U.V. dose requirements.

Effluent Criteria

State criteria for the disinfection of secondary treatment plant effluents typically cite fecal coliform densities as the primary indicator. These are generally expressed as a maximum 30-day geometric mean and a maximum 7-day geometric mean. Typically, the criteria specify a maximum 30-day mean fecal coliform density of 200 MPN/100 ml and a maximum 7-day mean fecal coliform density of 400 MPN/100 ml. These guidelines have been utilized by a majority of states when setting criteria for individual NPDES permit programs and are utilized within the context of this report for design and cost examples. Certainly, variations of these guidelines exist, dictated in specific cases by receiving water quality (assimilative capacity) and water use (recreational, shellfish harvesting, etc.). Separate analyses would be required to develop the design and costs for these particular applications.

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Plant Effluent Characteristics

Recall from Section 6 that the ultraviolet dose has been expressed as a function of the incident intensity, the lamp spacing, the system void volume, the flow, and the U.V. absorbance coefficient (at 253.7 nm). The lamp spacing, incident intensity, and void volume are set by the physical design of a specific system. Thus the design sizing for a U.V. system would be based on the requirement to achieve and maintain the dosage required to meet the effluent criteria at the critical conditions of flow and U.V. absorbance, that is, at the maximum 30-day and 7-day occurrences. This critical period would occur when variations in the flow and water quality combine to require the maximum ultraviolet energy input.

The one year record of flow and U.V. absorbance which had been obtained as part of the NW Bergen study was analyzed to provide an example of this critical design procedure. A record of thirty and seven day running averages was constructed for both flow and U.V. absorbance. Analysis of these data indicated maximum to average ratios of 1.8 and 1.9 for the 30-day and 7-day U.V. absorbance coefficient averages, respectively. The concurrent ratios for flow were 1.15 for both the 30-day and 7-day conditions.

Dose Requirement

The dose-response relationship shown on Figure 21 indicates that the dose required to achieve the maximum 30-day, mean effluent fecal coliform density of 200 MPN/100 ml is approximately 60,000 μW-sec/cm^2. A dose of approximately 43,000 μW-sec/cm^2 would be required to meet the 7-day criterion of 400 MPN/100 ml. Given the small difference in the max/avg. ratios between the 7-day and 30-day flow and U.V. absorbance conditions, and the fact that the dosage required for the 7-day criterion is 70% of the 30-day dose requirement, it was determined that the 30-day condition would control the sizing of the U.V. unit.

System Sizing

A series of design curves was developed which was specific to the unit specifications of the system at NW Bergen. The curves are displayed on Figure 34. These relate the total design power requirement to the annual average flow at various annual average absorbance coefficients. The 30-day criterion is assumed to control, as experienced at NW Bergen. The following is an example (NW Bergen) of the calculation used to develop the relationships on Figure 34,

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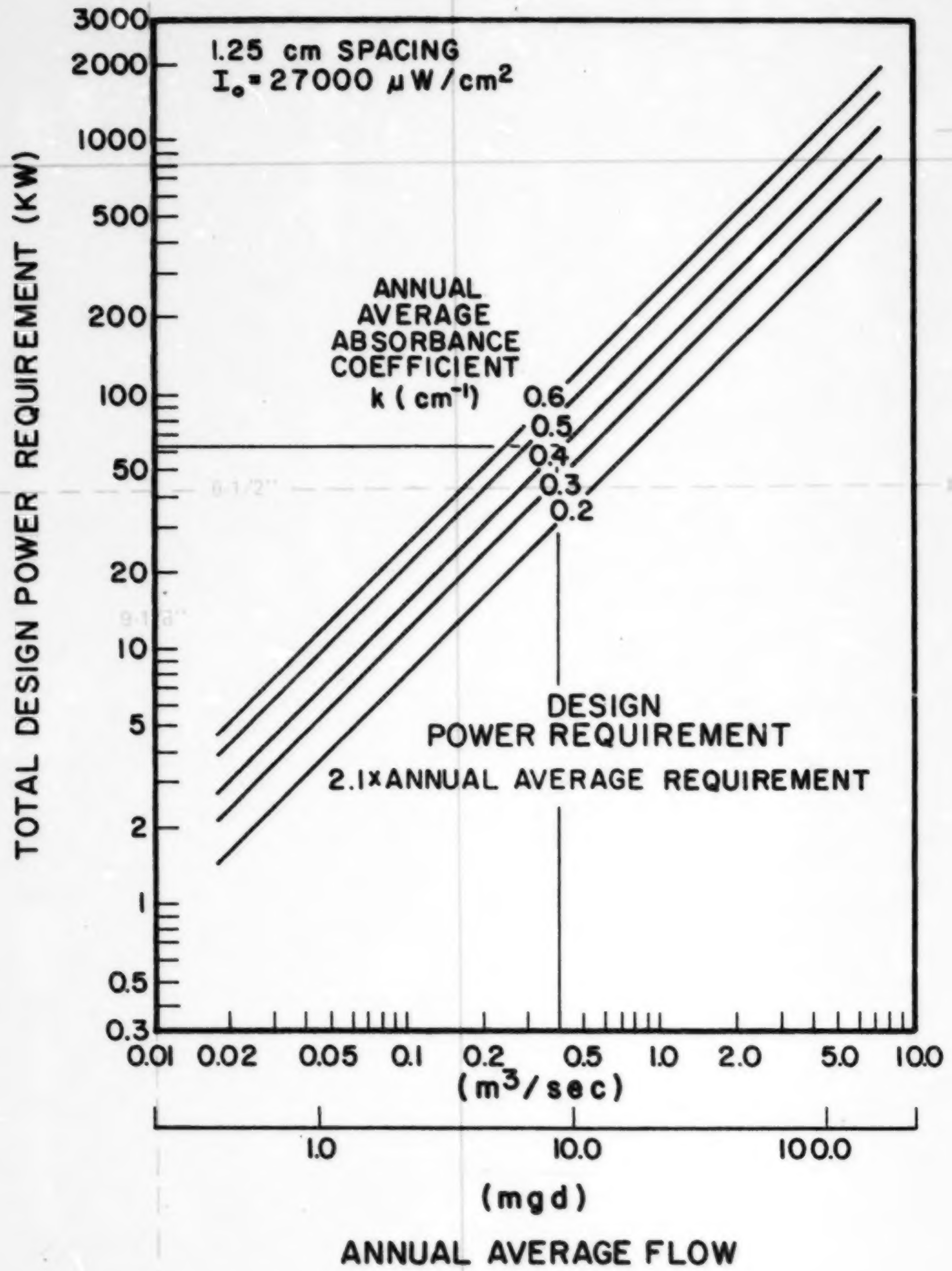

Figure 34. Ultraviolet system design example.

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Given

lamp spacing = 1.25 cm
annual average flow, Q = 0.4 m^3/sec
incident intensity, I_o = 27,000 μW/cm^2
void volume/lamp = 0.0012 m^3
annual average absorbance coefficient, k = 0.4 cm^{-1}
max 30-day k/annual average k = 1.8
equivalent 30-day period Q/annual Q = 1.15

From Figure 15, the compounding factor, F, is determined to be 2.0 at an absorbance coefficient 0.4 cm^{-1}. The critical 30-day F is then computed as,

$$2.0/1.8 = 1.11$$

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where 1.8 is the ratio of the max 30-day k to annual average k. The average intensity can then be computed as

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$$I_{avg} = I_o F$$

$$I_{avg} = 27{,}000 \times 1.11 = 30{,}000 \ \mu W\text{-}sec/cm^2$$

To meet a dose requirement of 60,000 μW-sec/cm^2, the exposure time is determined to be,

$$t_e = \frac{D}{I_{avg}}$$

$$t_e = 60{,}000/30{,}000 = 2 \text{ seconds.}$$

The void volume associated with each lamp and quartz enclosure for this system specification is 0.0012 m^3. At the design flow of

$$1.15 \times 0.4 \ m^3/sec = 0.46 \ m^3/sec$$

The required void volume is,

$$V_{void} = Q_{design} \times t_e$$

$$V_{void} = 0.46 \times 2 = 0.92 \ m^3$$

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Thus, the total lamp requirement is 767 (0.92 m^3 divided by 0.0012 m^3/lamp). At a nominal lamp rating of 85W the total power requirement is approximately 61 KW (as shown on Figure 34). The annual average power usage would be approximately 30-40 KW (61 KW divided by the combined flow and U.V. absorbance factor of 1.15 x 1.8 = 2.1). The curves presented on Figure 34 do not include any dose adjustment to compensate for photoreactivation.

SYSTEM DESIGN CONSIDERATIONS

Once the design ultraviolet dose has been determined and the system has been appropriately sized, there are several considerations which should be addressed in the design of a permanent full scale facility. These are summarized in the following discussions and are based on the experiences and observations derived from the NW Bergen field study. Certainly, as more experience is gained in the full scale application of the U.V. disinfection process, these will be refined and expanded.

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Pretreatment

Pre-screening of the wastewaters may be required for protection of the U.V. lamp battery. The experiences with algal blooms at N.W. Bergen have been described earlier. Fibrous material (such as sloughed algal growth) will catch on the quartz sleeves. If the system is equipped with a mechanical wiper system, the material will be swept to the sides, and compacted sufficiently to cause compression problems with the quartz enclosures. Pre-screening would eliminate this maintenance problem and would also prevent large pieces of debris entering the system and causing damage to the quartz.

The complexity of the pre-screening system would be related to plant size and wastewater conditions (i.e. the potential for problems to occur). It is expected that the normal requirement would be simple, manually controlled wide mesh (approximately 1-2 cm) screens placed in the U.V. influent channels.

Hydraulics

The hydraulics of the system must be evaluated and accounted for in terms of flow distribution and headloss. The potential for short-circuiting must be minimized by the design. The lamp battery should be completely submerged during operation. Flow direction should be perpendicular to the lamps, although this will cause a greater headloss and structural stress to the quartz enclosure. Surging should be minimized to avoid flooding or structural damage. Bypass weirs should be considered as well as a system which prevents a surge introduction of flow when a lamp system is brought into operation. The headloss associated

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with any pre-screening system would also have to be accounted for.

Cleaning

The cleaning system on the unit at N.W. Bergen was a mechanical wiper which proved to be very effective in maintenance and in preventing the buildup or accumulation of a film on the quartz surface. If the system was shutoff for a period of several days, however, and a film was allowed to accumulate on the quartz, the mechanical wiper did not appear to be capable of restoring the quartz to its original clarity and a film established itself on the surface. The quartz then required cleaning with an acid solution.

Systems available at present utilize cleaning procedures ranging from the mechanical wipers used in this study, to automated chemical cleaning, and to sonication. Selection should consider maintenance requirements, costs, and demonstrated effectiveness.

System Control

A dosage control system programmed to variations in the flow and ultraviolet absorbance is desirable and can allow a significant savings in power and expendable materials costs. Lamp battery operation can be modulated automatically as the flow varies, as an example. This could involve varying the number of lamps in operation, or the applied voltage.

System Monitoring

Monitoring of the unit would include, at minimum, flow (plant effluent meter would be sufficient), U.V. absorbance, and relative intensity. The power draw of each unit should also be monitored, as well as the operability of each lamp (pilot LED console). Continuous monitoring instrumentation for U.V. absorbance and U.V. intensity may be provided, particularly in the larger, more complex systems. This would allow greater control of the applied dose and should result in a materials and power savings.

Housing

A permanent structure is recommended to house the entire unit operation.

Accessibility

Accessibility to the system and all parts for maintenance is required. When space and costs allow, access galleries should be provided on either side of the lamp batteries: one side should have sufficient space to remove lamps from the units. An overhead crane system may also be provided to facilitate the occasional placement or removal of units, particularly in larger facilities.

Flexibility

Multi-unit systems should be designed with the ability to divert flow to any combination of units. Sufficient redundancy should also be provided to allow for the potential shut down of a reasonable fraction of the units during wastewater flow and quality conditions. At the lower design flow conditions where a single unit would be adequate, a replicate unit should be provided. Total replication would not be needed as the number of modular systems increases; i.e., the degree of replication should decrease as the number of systems increases.

The modular nature of ultraviolet disinfection systems lends itself well to staged construction. This aspect may be considered in the design of full-scale systems.

Safety

Since the eyes and skin readily absorb U.V. radiation, they are particularly vulnerable to injury. Sunburn (erythema) is a common example of the effect of U.V. radiation on the skin. Absorption by the mucous membranes of the eye and eyelids can cause conjunctivitis (commonly known as "ground glass eyeball" or "welders flash"). Injuries to the eye usually show up six to twelve hours after exposure and although painfull and incapacitating, the damage is usually temporary.

Because U.V. radiation is easily absorbed by a wide variety of materials, protection from over-dosage is normally accomplished in a straight-forward manner. Personal protection against radiation below 400 nm wavelength can be accomplished through the use of eyeglasses, goggles, plastic face shields, protective clothing, or sunscreen creams or lotions.

A lamp battery would not present a hazard while submerged and operational due to the high absorbability of the liquid. However, should the unit be engaged out of the water the radiation would be intense and transmissable for long distances, presenting an extreme hazard to anyone exposed. If it is necessary to engage the system under these circumstances it is absolutely necessary that the proper protective gear be worn by all personnel in the area and that adequate warning signals be active to warn anyone entering the area.

Other safety aspects to consider include safety railings, electrical interlocks, remote operating consoles, adequate electrical wiring, grounding, and waterproofing. Particular attention should be paid to materials of construction and their demonstrated resistance to attack by U.V. radiation and ozone.

ULTRAVIOLET DISINFECTION COSTS

Estimates were made of the capital and operational and maintenance costs associated with the application of the U.V. disinfection process to secondary wastewater treatment plant effluents. These costs are based on the information derived from the NW Bergen study and address the installation and operation of a new permanent facility. Retrofitting to an existing plant has not been considered, although the capital outlay would be lower in such a case.

The costs of a particular application are highly sensitive to the specific site characteristcs such as flow and water quality variability, and physical site conditions. As such, the estimates provided herein must be considered as preliminary when used to estimate the cost of a particular application. The estimates also provide a perspective when comparing the U.V. process to alternative disinfection procedures.

Figure 35 graphically summarizes the cost analysis which was conducted for a specific matrix of wastewater characteristics and equipment specifications. The costs are based in 1979, and were developed for the design of a "typical" secondary treatment plant. The average annual absorbance coefficient was assumed to be 0.5 cm^{-1} (recall that the average coefficient at NW Bergen was 0.4 cm^{-1}). The controlling effluent criterion was assumed to specify that the maximum thirty consecutive day geometric mean fecal coliform density not exceed 200 MPN/100 ml. The ratio of peak design to average design power requirement was assumed to be 2.1 (as shown on Figure 34), and the unit design assumes a nominal spacing of 1.25 cm, as was the case at NW Bergen. As shown on the abscissa of Figure 34, the design power requirements ranged from 10 to 1000 KW for annual average flows of 0.044 to 4.4 m^3/sec (1-100 mgd).

The following discussions detail the capital and O&M costs derived for a 100 KW system. These are provided in order to demonstrate the method by which the curves on Figure 35 were developed. Under the conditions described earlier, the 100 KW system is adequate for an annual average plant design flow of 0.44 m^3/sec, or 10 mgd.

Capital Costs

A summary of the capital costs associated with a 100 KW system is presented on Table 13. Equipment costs have been estimated on the basis of information (1979) provided by Pure Water Systems, Fairfield, N.J., manufacturers of the system utilized at NW Bergen. The equipment includes:

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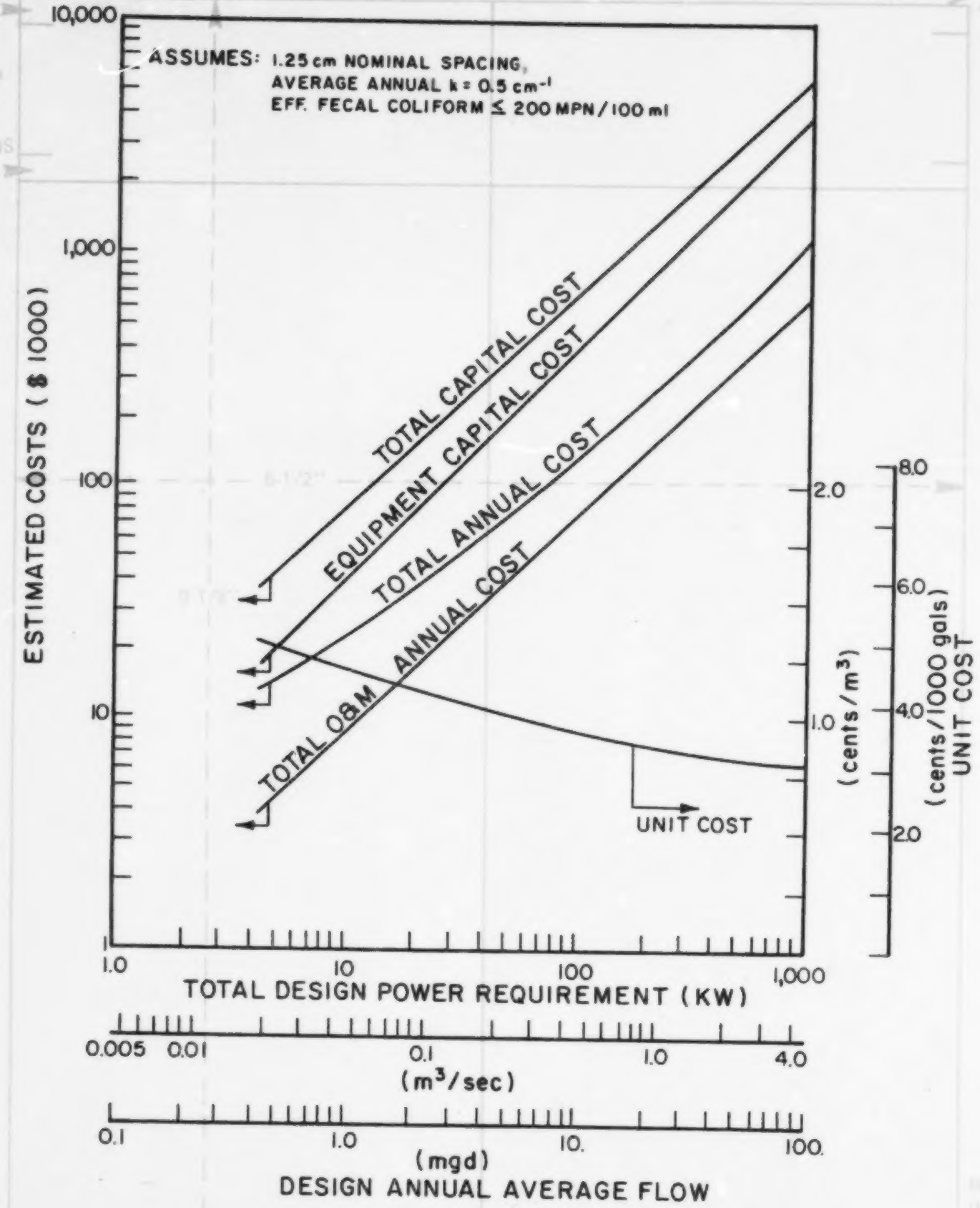

Figure 35. Cost example for U.V. installation.

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TABLE 13

CAPITAL COST EXAMPLE FOR 100 KW ULTRAVIOLET SYSTEM(1)

		Costs
U.V. Equipment		$ 440,000
(includes hardware, cleaning, screens, power supply, control and instrumentation)		
Construction-Structural		$ 130,000
Tankage (approx. 150 m^3)	$ 80,000	
Building (approx. 350 m^2)	$ 30,000	
Ancillary Equipment (crane, grating, weir, gates, etc.)	$ 20,000	
Installation (20% of equipment)		$ 88,000
(includes electrical supply, equipment, and instrumentation hookups)		
Engineering (10% of Structural & Installation)		$ 22,000
Contingency (30% of Structural)		$ 40,000
Total Estimated Capital Costs		$ 720,000

(1) Assumes a peak to average power requirement ratio of 2.1, 50% replication at peak, 1.25 cm spacing, an average absorbance coefficient of 0.5 cm^{-1}, and an effluent criterion of 200 MPN/100 ml (max 30-day mean fecal). EPA Index = 330.

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- ultraviolet system hardware with automatic wiper
- inlet screens
- power supply
- variable power control
- manufacturers engineering costs
- startup
- intensity monitor

The number of units installed is dependent upon the peak design requirement and the degree of replication appropriate to the particular application. For purposes of this discussion, a conservative approach has been taken in sizing the system. The degree of replication is considered high; with full scale applications and operating experience, the system design will be refined and may result in lower sizing requirements. In the example shown in Figure 35, replicate systems are provided at a peak design flow of 0.21 m^3/sec, each capable of treating the total flow. At a design flow of 0.44 m^3/sec 50 percent replication is provided. This means that although 70 KW is required at a flow of 0.44 m^3/sec, a total of approximately 100 KW is provided. At flows of 1.75 m^3/sec and greater, there is 25% replication. As indicated on Figure 35, the 100 KW system is estimated to have an equipment cost of $440,000.

Structural costs include concrete tankage, access ways between each lamp battery, influent and effluent channels, a building to house the entire unit operation, and ancillary equipment such as overhead cranes, grating, and utility hookups. Engineering is estimated at 10% of the structural and installation costs, and a contingency cost is estimated at 30% of the structural capital costs. Installation is estimated to be 20% of the equipment costs and includes the electrical supply. As shown on Table 13, the total capital cost for the 100 KW ultraviolet system is estimated to be $720,000. The precision of this estimate is considered to be +35% and -20%, providing a cost range of $575,000 to $970,000.

Operational and Maintenance Costs

Table 14 summarizes the O&M costs associated with the 100 KW system. As discussed earlier, the U.V. system is relatively simple and should require minimal labor for operation and maintenance. However, for purposes of this discussion, a conservative estimate of approximately 0.5 MY is assumed. Given the prototype nature of large scale U.V. systems and the lack of significant full-scale operating experience, this estimate is considered appropriate. At a rate of $80/MD, the labor cost is estimated to be $10,400.

Material costs include lamps, quartz enclosures, ballasts, wiper rings and miscellaneous expendable equipment parts. The system is assumed to use 85W germicidal lamps with a replacement

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TABLE 14

O&M COST EXAMPLE FOR 100 KW ULTRAVIOLET SYSTEM(1)

		Annual Costs
Labor; 130 MD		$ 10,400
Materials(2)		
Lamps; 125% replacement rate at $30/lamp	$23,000	
Quartz; 25% replacement rate; $25/unit	$ 7,500	
Ballasts; 25% replacement rate; $25/unit	$ 7,500	
Rings; 100% replacement rate; $1.25/unit	$ 1,500	
Miscellaneous (0.5% fixed capital)	$ 3,500	
Total Materials		$ 43,000
Power(3)		
Annual use of 416,000 KWH @ $0.045/KWH		$ 19,700
Total O&M Costs		$ 73,100

(1) Assumes a peak to average power requirement ratio of 2.1, 50% replication at peak, 1.25 cm spacing, an average absorbance coefficient of 0.5 cm^{-1}, and an effluent criterion of 200 MPN/100 ml (max 30-day mean fecal).

(2) Assumes 85W Germicidal lamps; replacement rates are on an annual basis.

(3) 1.05 x Annual average power requirement, which is the peak power requirement divided by 2.1.

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rate of 9 months. The quartz enclosures will solarize over a period of 3 to 4 years and require replacement. A replacement cycle of 25% per year is assumed for the quartz sleeves, as well as the lamp ballasts. The rings, based on the pilot study evaluation should be replaced each year. The miscellaneous materials (repairs, etc.) are assumed to be 0.5% of fixed capital. The total materials costs for the 100 KW system is $43,000/yr, as shown on Table 14.

Power costs are estimated on the basis of 1.05 times (to account for auxiliary power usage) the annual average power requirement. The annual average power requirement in this case is the peak power requirement (100 KW) divided by the peaking factor (2.1), or 47.6 KW. This translates to an annual power use of 437,850 KWH. Power costs are assumed to be 4.5 cents per KWH, which yields an annual power cost of $19,700 for the 100 KW system. As shown on Table 14, the annual O&M costs are $73,100 for the 100 KW system.

Table 15 is a summary of the capital and O&M costs derived for the ultraviolet disinfection process over a range of 10 - 1000 KW systems. The capital costs are amortized over 20 years at a rate of 6%. The total estimated annual costs were determined to range between $16,000 and $1,119,000/year, for system sizes between 10 and 1000 KW. This is equivalent to a unit cost of 1.2 to 0.8 cents/m^3 (4.5 to 3.0 cents/1000 gal), respectively.

As indicated by Table 15, the capital cost accounts for approximately 43% of the annual costs. Power accounts for approximately 12 to 17%, while labor represents 6 to 14%. Materials account for a major share of the annual costs, ranging between 28 and 35%.

COMPARISON OF COSTS FOR ALTERNATIVE DISINFECTION PROCESSES

Table 16 is a comparison of the U.V. disinfection unit costs with those reported for alternative disinfection processes. These costs have been derived from a variety of sources (1,49,50,51,52,53,54), and have been adjusted to 1979 based on the EPA national index (1979 = 330). In certain cases a wide range in cost estimates was found for a specific process (this was particularly the case for ozonation). The values presented on Table 16 represent an approximate average of the various estimates. Additionally, the costs presented in various sources may differ in the various assumptions for labor, power, etc. Caution is therefore warranted in any direct comparisons.

Figure 36 is a graphical presentation of the costs given on Table 16. As shown, U.V. disinfection appears to be particularly competitive at the lower flow levels. At a design flow of 0.044 m^3/sec (1 mgd) the U.V. cost is estimated to be 1.2¢/m^3

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TABLE 15

CAPITAL AND O&M COSTS ASSOCIATED WITH U.V. DISINFECTION PROCESS

Design Requirement (KW)	Equivalent[1] Annual Flow (mgd)	Equivalent[1] Annual Flow (m^3/sec)	Capital Costs (dollars)	Annual O&M Costs (dollars) Labor	Annual O&M Costs (dollars) Materials	Annual O&M Costs (dollars) Power	Total O&M
10	1	0.044	80,000	2500	4,500	2000	9000
100	10	0.44	700,000	10500	43,000	19700	73200
1000	100	4.4	5,200,000	70000	400,000	197000	667000

Design Requirement (KW)	Amortized[2] Capital Costs	Total. Annual Cost	Unit Cost ¢/1000 gal	Unit Cost ¢/m^3
10	7900	16,000	4.5	1.2
100	60800	134,000	3.6	0.95
1000	451400	1,119,000	3.0	0.8

(1) Assumes: k = 0.5 cm^{-1} (average); peaking factor = 2.1; 100% replication at 10 KW, 50% at 100 KW, 25% at 1000 KW; 1.25 cm spacing; max 30-day mean fecal coliform density not to exceed 200 MPN/100 ml.

(2) 20 years at 6% (CRF = 0.087)

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TABLE 16

COMPARISON OF UNIT COSTS ASSOCIATED WITH ALTERNATIVE DISINFECTION PROCESSES(1)

	Unit Cost (¢/m^3)		
Design Flow (m^3/sec)	0.044	0.44	4.4
Process			
Ultraviolet Irradiation	1.2	0.95	0.8
Chlorination	1.7	0.74	0.58
Chlorination/Dechlorination (SO_2)	2.2	0.82	0.60
Ozonation (from air)	3.4	2.0	1.45
Chlorobromination	1.6	0.61	0.35

(1) References 1, 49, 50, 51, 52, 53, 54

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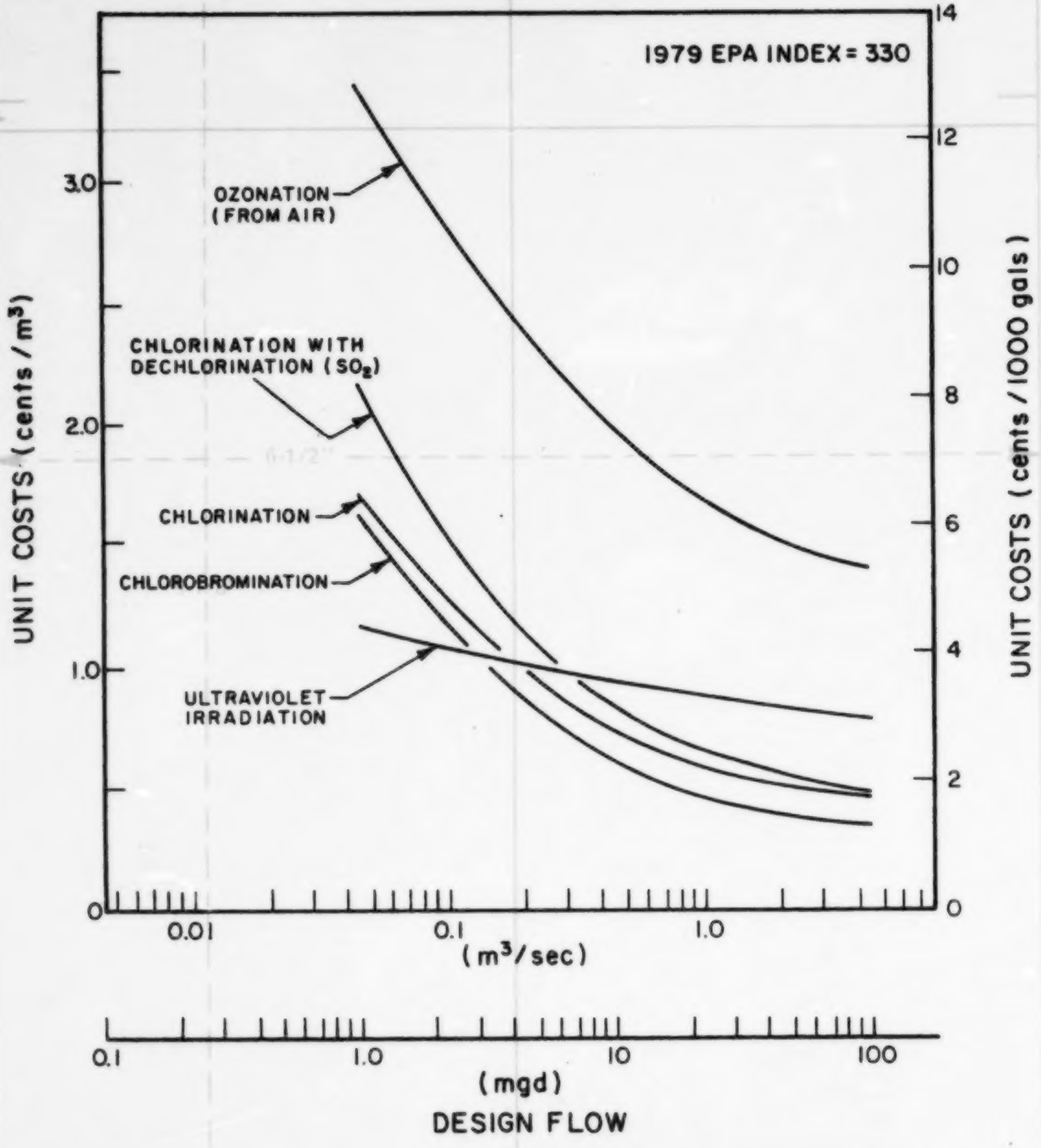

Figure 36. Comparison of unit costs for alternative disinfection processes.

(4.5¢/1000 gal). Chlorination is estimated to cost approximately 1.7¢/m^3 (6.4¢/1000 gal) at this design flow, while chlorination with subsequent dechlorination (with SO_2) is 2.2 ¢/m^3 (8.3¢/1000 gal) and ozonation (from air) is 3.4¢/m^3 (12.9¢/1000 gal). As the design flow increases, U.V. disinfection is estimated to be comparable in cost to chlorination, chlorobromination, and chlorination/dechlorination, and considerably less than ozonation.

IMPACT OF PHOTOREACTIVATION ON U.V. DISINFECTION COSTS

The analysis of the costs associated with ultraviolet disinfection did not consider the impact of photoreactivation, since existing standards do not consider repair (or aftergrowth) phenomena in setting effluent bacterial density levels. An estimate can be made however, of the potential increase in costs which may be incurred if photoreactivation were to be considered a factor in the process design.

The critical period for photoreactivation would be in the summer months, since the mechanism is sensitive to temperature. At a temperature of 25°C, Equation 8-3 (photoreactivation dose-response regression) of Section 8 would predict that a dose of 264,000 μW-sec/cm^2 would be required to achieve the fecal coliform density level of 200 MPN/100 ml. Equation 7-9 (non-photoreactivation dose-response regression) of Section 7 predicts that a dose of 57,000 μW-sec/cm^2 would be required. Thus, accounting for photoreactivation would require a 460% increase in system sizing. This has a direct impact on the capital cost, which represents approximately 43% of the annual costs associated with ultraviolet disinfection.

The O&M costs would also increase, although not as much as the capital costs, depending on the temperature variations through the year. Assuming a northern climate, as with the NW Bergen study, the dose increment would range between 1.2 to 4.6 times the non-photoreactivation dose for winter and summer conditions, respectively. For purposes of this analysis, it has been assumed that the O&M costs (which account for approximately 57% of the annual costs) would increase by a factor of 2.

Thus the overall increase in costs may be estimated as 4.6 x 43% of the total annual cost, plus 2.0 x 57% of the total annual cost. This yields a factor of 3.1 times the annual estimated costs associated with U.V. disinfection. This would increase the unit costs on Table 15 to 3.72 cents/m^3 (13.6¢/1000 gals) for a 10 KW system, and 2.5¢ (9.3¢/1000 gals) for a 1000 KW system. Such costs would be comparable to present estimates for ozone disinfection with no aftergrowth considerations.

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APPENDIX A

OPERATIONAL LOG

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TABLE A-1

SUMMARY OUTLINE OF UV OPERATION AND MAINTENANCE CONDITIONS DURING THE TOTAL FIELD STUDY

Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	1	3/6/78	Full power - all lamps
	2	3/7/78	Full power - all lamps
	3	3/8/78	Full power - all lamps
	4	3/9/78	Full power - all lamps
	5	3/10/78	Full power - all lamps
	6	3/11/78	Full power - all lamps
	7	3/12/78	Full power - all lamps
1	8	3/13/78	Unit lifted out of channel to inspect wiper tow gland and replace defective pilot light indicators for UV lamps (replacing incandescent with L.E.D.). Wiper stroke found to be 9" short on each end.
2	9	3/14/78	Dissassembled quartz to provide access to wiper retaining nut for cable. Removed wiper assembly.
3	10	3/15/78	Worked on wiper retaining nut
4	11	3/16/78	Worked on wiper mechanism
5	12	3/17/78	Replaced wiper mechanism; reassembled unit
6	13	3/18/78	Placed unit in channel, checked wiper operation
7	14	3/19/78	Checked electrical
	15	3/20/78	Full power - all lamps
	16	3/21/78	Full power - all lamps
	17	3/22/78	Full power - all lamps
	18	3/23/78	Full power - all lamps
	19	3/24/78	Full power - all lamps
8	20	3/25/78	Wiper cable slipped causing leak at seal gland. Sump pump malfunctioned causing flooding of unit; electrical shorting, and burning of lamp harness; unit removed from channel.

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TABLE A-1
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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
9	21	3/26/78	Repairing wiper cable
10	22	3/27/78	Repairing wiper cable
11	23	3/28/78	Repairing wiper mechanism - rewiring harnesses
12	24	3/29/78	Reinstalled unit - electrical checks
	25	3/30/78	Operating
	26	3/31/78	Operating
13	27	4/1/78	Major short in UV system - about 100 tubes broken
14	28	4/2/78	System down
15	29	4/3/78	System down
16	30	4/4/78	System down
17	31	4/5/78	System down
18	32	4/6/78	System down
19	33	4/7/78	System down
20	34	4/8/78	system down
21	35	4/9/78	System down
	36	4/10/78	Full power - all lamps
	37	4/11/78	Vary power - all lamps
	38	4/12/78	Full power - all lamps
	39	4/13/78	Full power - all lamps
	40	4/14/78	Full power - all lamps
	41	4/15/78	Full power - all lamps
	42	4/16/78	Full power - all lamps
	43	4/17/78	Full power - all lamps
	44	4/18/78	Full power - all lamps
	45	4/19/78	Full power - all lamps
22	46	4/20/78	Electrical short in amphenol connector - burned wire (water in plug); rewired
	47	4/21/78	Full power - all lamps
	48	4/22/78	Full power - all lamps
	49	4/23/78	Full power - all lamps
	50	4/24/78	Full power - all lamps
	51	4/25/78	Full power - all lamps
	52	4/26/78	Full power - all lamps
	53	4/27/78	Full power - all lamps
	54	4/28/78	Full power - all lamps
	55	4/29/78	Operating

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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	56	4/30/78	Operating
	57	5/1/78	Full voltage - all lamps
	58	5/2/78	Vary voltage - all lamps
	59	5/3/78	Full voltage - all lamps
	60	5/4/78	Full voltage - all lamps
	61	5/5/78	Full voltage - all lamps
	62	5/6/78	Full voltage - all lamps
	63	5/7/78	Full voltage - all lamps
	64	5/8/78	Full voltage - all lamps
	65	5/9/78	Full voltage - all lamps
	66	5/10/78	Full voltage - all lamps
	67	5/11/78	Full voltage - all lamps - replaced defective pilot light bulbs
23	68	5/12/78	Unit removed from channel to replace inoperative U.V. lamps
	69	5/13/78	Operating, Bank "B"
	70	5/14/78	Operating, Bank "B"
	71	5/15/78	Operating, Bank "B"
	72	5/16/78	Operating, Bank "B"
	73	5/17/78	Operating, Bank "B"
	74	5/18/78	Operating, Bank "B"
	75	5/19/78	Operating, Bank "B"
	76	5/20/78	Operating, Bank "B"
	77	5/21/78	Operating, Bank "B"
24	78	5/22/78	Checked electrical system and lamps
25	79	5/23/78	Electrical shorts on amphenol plugs - unit shutdown
26	80	5/24/78	Repaired electrical damage
27	81	5/25/78	Repaired damage
28	82	5/26/78	Reassembled harness - checked electrical
29	83	5/27/78	Electrical check
	84	5/28/78	Power off - wipers on
	85	5/29/78	Power off - wipers on
	86	5/30/78	Full voltage - vary lamps
	87	5/31/78	Vary voltage - all lamps

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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	88	6/1/78	Full voltage - Bank "B"
	89	6/2/78	Full voltage - Bank "A"
	90	6/3/78	Operational
	91	6/4/78	Operational
	92	6/5/78	June series (vary voltage - all lamps)
	93	6/6/78	June series sampling followed with 75% voltage on Bank "H"
	94	6/7/78	75% voltage - Bank "H"
	95	6/8/78	75% voltage - Bank "H"
	96	6/9/78	75% voltage - all lamps
	97	6/10/78	75% voltage - all lamps
	98	6/11/78	75% voltage - all lamps
	99	6/12/78	June series sampling followed with full voltage Bank "H"
	100	6/13/78	Full voltage - Bank "H"
	101	6/14/78	Full voltage - Bank "H"
	102	6/15/78	Full voltage - Bank "H"
	103	6/16/78	Full voltage - Bank "H"
	104	6/17/78	Full voltage - Bank "H"
	105	6/18/78	Full voltage - Bank "H"
	106	6/19/78	June series sampling followed with 70% voltage all lamps
	107	6/20/78	June series sampling followed with 70% voltage all lamps
	108	6/21/78	70% voltage all lamps
	109	6/22/78	70% voltage all lamps
30	110	6/23/78	Shut down unit to clean tanks
	111	6/24/78	All lamps
	112	6/25/78	70% voltage - all lamps
	113	6/26/78	June series sampling followed with 70% voltage all lamps
	114	6/27/78	June series sampling followed with 70% voltage all lamps
	115	6/28/78	70% voltage - all lamps
	116	6/29/78	70% voltage - all lamps
	117	6/30/78	70% voltage - all lamps

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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	118	7/1/78	70% voltage - all lamps
	119	7/2/78	70% voltage - all lamps
	120	7/3/78	70% voltage - all lamps
	121	7/4/78	70% voltage - all lamps
	122	7/5/78	70% voltage - all lamps
	123	7/6/78	70% voltage - all lamps
	124	7/7/78	70% voltage - all lamps
	125	7/8/78	70% voltage - all lamps
	126	7/9/78	70% voltage - all lamps
	127	7/10/78	50% voltage - all lamps
	128	7/11/78	50% voltage - all lamps
	129	7/12/78	40% voltage - all lamps
	130	7/13/78	90% voltage - all lamps
	131	7/14/78	75% voltage - all lamps
	132	7/15/78	75% voltage - all lamps
	133	7/16/78	75% voltage - all lamps
	134	7/17/78	75% voltage - all lamps
	135	7/18/78	75% voltage - all lamps
	136	7/19/78	75% voltage - all lamps
	137	7/20/78	75% voltage - all lamps
	138	7/21/78	75% voltage - all lamps
	139	7/22/78	75% voltage - all lamps
	140	7/23/78	75% voltage - all lamps
	141	7/24/78	July/Aug. series
	142	7/25/78	July/Aug. series sampling followed with 75% voltage - all lamps
	143	7/26/78	75% voltage - all lamps
	144	7/27/78	75% voltage - all lamps
	145	7/28/78	System drained to move the chlorine injector 15 feet downstream
	146	7/29/78	40% voltage - all lamps
	147	7/30/78	40% voltage - all lamps
	148	7/31/78	July/Aug. series sampling followed with 40% voltage Banks A, C, H

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TABLE A-1
(Continued)

Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	149	8/1/78	July/Aug. series sampling followed with 75% voltage - all lamps
	150	8/2/78	80% voltage - all lamps
	151	8/3/78	80% voltage - all lamps
	152	8/4/78	80% voltage - all lamps
	153	8/5/78	100% voltage - all lamps
	154	8/6/78	80% voltage - all lamps
	155	8/7/78	July/Aug. series sampling followed with 80% voltage - all lamps
	156	8/8/78	July/Aug. series sampling followed with 75% voltage - all lamps
	157	8/9/78	75% voltage - all lamps
	158	8/10/78	75% voltage - all lamps
	159	8/11/78	75% voltage - all lamps
	160	8/12/78	75% voltage - all lamps
	161	8/13/78	75% voltage - all lamps
	162	8/14/78	July/Aug. series sampling followed by tank draining to inspect quartz for wiper effectiveness - quartz clean - followed with 100% voltage - all lamps
	163	8/15/78	July/Aug. series sampling followed with 100% voltage - all lamps
	164	8/16/78	Full voltage - all lamps
	165	8/17/78	Full voltage - all lamps
	166	8/18/78	Full voltage - all lamps
	167	8/19/78	80% voltage - all lamps
	168	8/20/78	80% voltage - all lamps
	169	8/21/78	80% voltage - all lamps
	170	8/22/78	80% voltage - all lamps
	171	8/23/78	80% voltage - all lamps
	172	8/24/78	Full voltage - all lamps
	173	8/25/78	Full voltage - all lamps
	174	8/26/78	80% voltage - all lamps
	175	8/27/78	80% voltage - all lamps
	176	8/28/78	Full voltage - all lamps - Oakridge testing
	177	8/29/78	75% voltage - all lamps

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ABLE A-1
(Continued)

Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	178	8/30/78	Full voltage - all lamps
	179	8/31/78	Full voltage - all lamps
	180	9/1/78	Full voltage - all lamps
	181	9/2/78	Full voltage - all lamps
	182	9/3/78	Full voltage - all lamps
	183	9/4/78	Full voltage - all lamps
	184	9/5/78	Full voltage - all lamps
32	185	9/6/78	Shut down - algae slugs caught in unit blocking full wiper action - unit pulled out of channel to remove algae and replace inoperative UV lamps
33	186	9/7/78	Continue lamp replacement - calibration of V notch weir by B.I.F. (39 lamps replaced)
34	187	9/8/78	System down
35	188	9/9/78	System down
36	189	9/10/78	System down
37	190	9/11/78	Two quartz tubes broken by packed in algae
38	191	9/12/78	Cleaning out algae - check lamp output
39	192	9/13/78	Start up - after 1 day quartz broke-algae in unit
40	193	9/14/78	Repairing broken quartz
41	194	9/15/78	System down
42	195	9/16/78	System down
43	196	9/17/78	Cleaning algae out of unit and influent channels
44	197	9/18/78	System down
45	198	9/19/78	System down
46	199	9/20/78	System down
47	200	9/21/78	System down
48	201	9/22/78	System down
49	202	9/23/78	Reassembled lamps in unit
	203	9/24/78	Start up full voltage all lamps
	204	9/25/78	Full voltage - all lamps
	205	9/26/78	75% voltage - all lamps
	206	9/27/78	Full voltage - all lamps
	207	9/28/78	Full voltage - all lamps

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
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TABLE A-1
(Continued)

Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	208	9/29/78	Full voltage - all lamps
	209	9/30/78	Full voltage - all lamps
	210	10/1/78	Full voltage - all lamps; suspect heavy rains blowing behind tarp shorted out phase A resulting in 'A' and 'H' banks receiving about 50% power
	211	10/2/78	Full voltage banks B, C, D, F; about 50% voltage banks A and H
	212	10/3/78	Full voltage all banks; A and H at about 50% voltage
	213	10/4/78	Full voltage all banks; A and H at about 505 voltage
	214	10/5/78	Full voltage all banks; A and H at about 50% voltage
	215	10/6/78	Full voltage all banks; A and H at about 50% voltage
	216	10/7/78	Full voltage all banks; A and H at about 50% voltage
	217	10/8/78	Full voltage all banks; A and H at about 50% voltage
	218	10/9/78	Full voltage all banks; A and H at about 50% voltage - found short noted above (10/1) replaced fuses, checked lamps
	219	10/10/78	Full voltage - all lamps - estimate of 50-100 lamps out
	220	10/11/78	Full voltage - all lamps - routine sampling (several lamps out)
	221	10/12/78	Full voltage - all lamps - routine sampling (several lamps out); Bank A giving low intensity reading
50	222	10/13/78	Shut down - pulled unit out of channel - electrical checks
51	223	10/14/78	Electrical checks and repairs
52	224	10/15/78	Electrical checks and repairs
53	225	10/16/78	Electrical checks and repairs - replace bad lamps and ballasts

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(Continued)

Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
54	226	10/17/78	Replace bad lamps and ballasts
	227	10/18/78	Full voltage - all lamps
	228	10/19/78	Full voltage - all lamps
	229	10/20/78	Full voltage - all lamps
	230	10/21/78	Full voltage - all lamps
	231	10/22/78	Full voltage - all lamps
	232	10/23/78	Full voltage - all lamps
	233	10/24/78	Full power all lamps - replaced #7 electrical harness because of a short in the amphenol plug - probably due to moisture
	234	10/25/78	Full power - all lamps
	235	10/26/78	Full power - all lamps
	236	10/27/78	Full power - all lamps
	237	10/28/78	Full power - all lamps
	238	10/29/78	Full power - all lamps
	239	10/30/78	Full power - all lamps
	240	10/31/78	Full power Banks A, B, C
	241	11/1/78	Full power all Banks
	242	11/2/78	Shut down - replace 2 harnesses with new, one piece teflon wire design - all harnesses now have this design; followed with full voltage all lamps; work duration 9 am - 3 pm (about 6 hours)
	243	11/3/78	Voltage off
	244	11/4/78	Full power - all lamps
	245	11/5/78	Full power - all lamps
	246	11/6/78	Full power - all lamps - wipers off
	247	11/7/78	Full power - all lamps - wipers off
	248	11/8/78	Full power - all lamps - wipers off
	249	11/9/78	Full power - all lamps - wipers off
	250	11/10/78	Full power - all lamps - wipers off
	251	11/11/78	Full voltage - all lamps - wipers off
	252	11/12/78	Full voltage - all lamps - wipers off
	253	11/13/78	Full voltage - all lamps - wipers off
	254	11/14/78	Full voltage - all lamps - wipers off
	255	11/15/78	Full voltage - all lamps - wipers turned on

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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	256	11/16/78	Full voltage - all lamps - lamps cleaned chemically; wipers on - unit drained
55	257	11/17/78	Unit down for electrical check
	258	11/18/78	Full voltage - all lamps - some lamps replaced
	259	11/19/78	Full voltage - all lamps
	260	11/20/78	Full voltage - all lamps
	261	11/21/78	Full voltage - all lamps
	262	11/22/78	Full voltage - all lamps
	263	11/23/78	Full voltage - all lamps
	264	11/24/78	Full voltage - all lamps
	265	11/25/78	Full voltage - all lamps
	266	11/26/78	Full voltage - all lamps
	267	11/27/78	Full voltage - all lamps
	268	11/28/78	Full voltage - all lamps
	269	11/29/78	Full voltage - all lamps
	270	11/30/78	Full voltage - all lamps
	271	12/1/78	Full voltage - all lamps
	272	12/2/78	Full voltage - all lamps
	273	12/3/78	Full voltage - all lamps
	273	12/4/78	Full voltage - all lamps
	275	12/5/78	Full voltage - all lamps
	276	12/6/78	Full voltage - all lamps
	277	12/7/78	Full voltage - all lamps
	278	12/8/78	Full voltage - all lamps
	279	12/9/78	Full voltage - all lamps
	280	12/10/78	Full voltage - all lamps; unit drained to determine reason for low intensity readings - algae film had developed on bulbs - cleaned and reinstalled - 3 hours
	281	12/11/78	Full voltage - all lamps - routine sampling
	282	12/12/78	Full voltage - all lamps - routine sampling

TABLE A-1
(Continued)

Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	283	12/13/78	Full voltage - all lamps - routine sampling
	284	12/14/78	Full voltage - all lamps - routine sampling
	285	12/15/78	Full voltage - all lamps
	286	12/16/78	Full voltage - all lamps
	287	12/17/78	Full voltage - all lamps
	288	12/18/78	Full voltage Banks A and B
	289	12/19/78	50% voltage Banks A and B; air line to wiper had frozen moisture clogging supply, resulting in no wiper action - probably from night before - this was corrected at noon
	290	12/20/78	Full voltage - all lamps - water frozen in air line - no wipers
	291	12/21/78	Full voltage - all lamps - wipers on
	292	12/22/78	Full voltage - all lamps
	293	12/23/78	Full voltage - all lamps
	294	12/24/78	Full voltage - all lamps
	295	12/25/78	Full voltage - all lamps
	296	12/26/78	Full voltage - all lamps
	297	12/27/78	Full voltage - all lamps
	298	12/28/78	Full voltage - all lamps
	299	12/29/78	Full voltage - all lamps
	300	12/30/78	Full voltage - all lamps
	301	12/31/78	Full voltage - all lamps
	302	1/1/79	Full voltage - all lamps
	303	1/2/78	Full voltage - all lamps
	304	1/3/79	Full voltage - all lamps; wipers inoperative for a while - ice in air line
	305	1/4/79	Full voltage - all lamps - wipers running off portable air compressor
	306	1/5/79	Full voltage - all lamps - wipers off because of ice in airline. Drained unit to check for film-none apparent

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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
56	307	1/6/79	Portable air compressor caused circuit breaker to go off - this disengaged sump pump, which back-siphoned and flooded UV unit. Unit was removed, plugs were dried - no damage - UV lamps out on 12/28/78 inventory were replaced
57	308	1/7/79	Work on air lines - wrapping to insulate
58	309	1/8/79	System down
59	310	1/9/79	System down
60	311	1/10/79	System down
61	312	1/11/79	System down
	313	1/12/79	Full voltage - all lamps
	314	1/13/79	Full voltage - all lamps
	315	1/14/79	Full voltage - all lamps
	316	1/15/79	Full voltage - all lamps
	317	1/16/79	Full voltage - all lamps
	318	1/17/79	Full voltage - all lamps
	319	1/18/79	Full voltage - all lamps
	320	1/19/79	Full voltage - all lamps; wiper stopped - ice in line - thawed - OK again
	321	1/20/79	Full voltage - all lamps
	322	1/21/79	Full voltage - all lamps
	323	1/22/79	Full voltage - all lamps
	324	1/23/79	Full voltage - all lamps
	325	1/24/79	Full voltage - all lamps
	326	1/25/79	Full voltage - all lamps - wipers inoperative - line frozen - thawed, OK
	327	1/26/79	Full voltage - all lamps
	328	1/27/79	Full voltage - all lamps
	329	1/28/79	Full voltage - all lamps
	330	1/29/79	Full voltage - all lamps
	331	1/30/79	Full voltage - all lamps
	332	1/31/79	Full voltage - all lamps

TABLE A-1
(Continued)

Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	333	2/1/79	Full voltage - all lamps - no wiper action - line frozen - removed, thawed, replaced
	334	2/2/79	Full voltage - all lamps
	335	2/3/79	Full voltage - all lamps
	336	2/4/79	Full voltage - all lamps
	337	2/5/79	Full voltage - all lamps (varying lamp banks)
	338	2/6/79	Full voltage - varying lamps - wipers inoperative part of the time
	339	2/7/79	Full voltage - all lamps
	340	2/8/79	Full voltage - all lamps
	341	2/9/79	Full voltage - all lamps
	342	2/10/79	Full voltage - all lamps
	343	2/11/79	Full voltage - all lamps
	344	2/12/79	Full voltage - varying lamps - wipers frozen but repaired
	345	2/13/79	Full voltage - varying lamps - wipers intermittant - ice in air line
	346	2/14/79	Full voltage - varying lamps - ice in line
	347	2/15/79	Full voltage - all lamps - wipers off - ice in line
	348	2/16/79	Full voltage - all lamps - wipers intermittent - ice in line
	349	2/17/79	Full voltage - all lamps - wipers off - ice in air line
	350	2/18/79	Full voltage - all lamps - wipers off - ice in air line
	351	2/19/79	Full voltage - all lamps - wipers off - ice in air line
	352	2/20/79	Full voltage - all lamps - wipers off - ice in air line
	353	2/21/79	Full voltage 3 lamp banks
	354	2/22/79	Full voltage 2 lamp banks
	355	2/23/79	Full voltage 1 lamp bank

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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	356	2/24/79	Full voltage - all lamps
62	357	2/25/79	Shut down - replaced 80 lamps - new
63	358	2/26/79	Shutdown
64	359	2/27/79	Shutdown
65	360	2/28/79	Shutdown
66	361	2/29/79	Shutdown
66	361	3/1/79	Shutdown
67	362	3/2/79	Shutdown
68	363	3/3/79	Shutdown
	364	3/4/79	Start up at 7:30 pm (1930 hrs)
	365	3/5/79	Varying voltage - all lamps
	366	3/6/79	Varying voltage - all lamps
	367	3/7/79	Varying voltage - all lamps
	368	3/8/79	Full voltage - all lamps
	369	3/9/79	Full voltage - all lamps
	370	3/10/79	Full voltage - all lamps
	371	3/11/79	Full voltage - all lamps
	372	3/12/79	Varying voltage - all lamps
	373	3/13/79	Full voltage - all lamps
	374	3/14/79	Varying voltage - all lamps
	375	3/15/79	Full voltage - all lamps
	376	3/16/79	Full voltage - all lamps
	377	3/17/79	Full voltage - all lamps
	378	3/18/79	Full voltage - all lamps
	379	3/19/79	Varying voltage - all lamps
	380	3/20/79	Varying voltage - all lamps
	381	3/21/79	Varying voltage - all lamps
	382	3/22/79	Full voltage - all lamps
	383	3/23/79	Full voltage - all lamps
	384	3/24/79	Full voltage - all lamps
	385	3/25/79	Full voltage - all lamps
	386	3/26/79	Full voltage - all lamps (during this week connectors to the lamps that were out were repaired)
	387	3/27/79	Full voltage - all lamps
	388	3/28/79	Full voltage - all lamps

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Cumulative No. of Downtime Days	Total No. of Days	Date	Operations & Maintenance Conditions - Comments
	389	3/29/79	Full voltage - all lamps
	390	3/30/79	Full voltage - all lamps
	391	3/31/79	Full voltage - all lamps
	392	4/1/79	Full voltage - all lamps
	393	4/2/79	Varying voltage - all lamps
	394	4/3/79	Varying voltage - all lamps
	395	4/4/79	Varying voltage - all lamps
	396	4/5/79	Full voltage - varied lamp banks
	397	4/6/79	Full voltage - all lamps
	398	4/7/79	Full voltage - all lamps
	399	4/8/79	Full voltage - all lamps
	400	4/9/79	Varying voltage - all lamps
	401	4/10/79	Varying voltage - all lamps
	402	4/11/79	Varying voltage - all lamps
	403	4/12/79	Full voltage - all lamps
	404	4/13/79	Full voltage - all lamps
	405	4/14/79	Full voltage - all lamps
	406	4/15/79	Full voltage - all lamps till 8 pm; Banks D thru H off for Monday (next day)
	407	4/16/79	Full voltage, 3 lamp banks
	408	4/17/79	Full voltage, 2 lamp banks
	409	4/18/79	Full voltage, 1 lamp bank

End of Field Studies

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